8-2005

A Tree-Ring Oxygen Isotope Record of Tropical Cyclone Activity, Moisture Stress, and Long-term Climate Oscillations for the Southeastern U.S.

Dana Lynette Miller
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Dana Lynette Miller entitled "A Tree-Ring Oxygen Isotope Record of Tropical Cyclone Activity, Moisture Stress, and Long-term Climate Oscillations for the Southeastern U.S.." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geology.

Claudia I. Mora, Henri D. Grissino-Mayer, Major Professor

We have read this dissertation and recommend its acceptance:

Maria E. Uhle, Theodore C. Labotka

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Dana Lynette Miller
August 2005

Acknowledgements

This research was funded in part by a National Science Foundation Grant (BCS-0327280) that was awarded to co-principle investigators Drs. Claudia I. Mora and Henri D. Grissino-Mayer entitled " Oxygen Isotope Compositions of Tree-Ring Cellulose as a High-Resolution Proxy Record of Hurricane Activity".

Abstract

Geological proxies are needed to extend the record of hurricane occurrence beyond historical observations. Tree rings preserve uniquely high resolution and precisely dated records of past environmental conditions. Oxygen isotopic compositions of alpha cellulose in seasonally-resolved components (earlywood (EW) and latewood (LW)) of tree rings of southeastern coastal plain pines predominantly reflect precipitation source and/or temperature providing a snapshot of climate activity for the region. Tropical cyclones produce large amounts of precipitation with distinctly lower oxygen isotope ratios than typical low-latitude thunderstorms. Evidence of isotopically depleted precipitation may persist in surface and soil waters for several weeks after a large event, and will be incorporated into cellulose during tree growth, capturing an isotopic record of tropical cyclone activity.

A 227-year record of EW and LW oxygen isotope compositions of alpha cellulose in slash and longleaf pine (*Pinus palustris* Mill. and *Pinus elliottii* Engelm.) tree rings record evidence of past tropical cyclone activity, seasonal moisture stress, and multidecadal climate oscillations. The isotopic values for EW and LW are overprinted on systematic, decadal to multi-decadal-scale variations. Negative isotopic anomalies in the time series, interpreted as hurricane events, were identified using a one-year autoregression modeling technique. Hurricane occurrence inferred from the oxygen isotope proxy compare well with the instrumental record of hurricanes over the period 1940-1997. The proxy record further supports historical records back to 1770 and suggests a number of possible tropical cyclone events not captured by documentary evidence. The results suggest the potential for a tree-ring oxygen isotope proxy record,

extending back many centuries, of long-term trends in hurricane occurrence. Records of seasonal moisture stress, inferred from positive isotopic anomalies in the isotopic time series are similarly tested and yield a robust record of moisture stress in the study area.

Long-term variations in the oxygen isotope compositions of tree-ring alpha cellulose are governed by the influence of long-term climate oscillations, including the Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, and El Niño Southern Oscillation. The Atlantic Multidecadal Oscillation (AMO) shows a strong negative correlation with tree ring $\delta^{18}O$ values until ~1950s. The breakdown in the correlation with the AMO coincides with a major Pacific Decadal Oscillation-El Niño Southern Oscillation shift from warm to cool conditions (1947–1976 Cool Period II) that was followed by two of the strongest La Niña episodes in the last 50 years. Latewood tree-ring oxygen isotopes from the decade of the 1950s strongly correlate with Niño 3.4 indices. Spectral analysis of the latewood tree-ring oxygen isotopes reveal significant periodicities of ~82.7, 33.7, 7.9, and 5.1 years. These periodicities may reflect solar activity such as the Gleissberg Period (82.7) and the Bruckner Cycle (33.7) and El Niño Southern Oscillation (7.9 and 5.1) influences on climate of the southeastern U.S. Five-to-six and seven-to-nine year periodicities have been related to the frequency of tropical-only and baroclinically enhanced Atlantic hurricanes.

Oxygen isotopes from tree-ring cellulose of sub-fossil longleaf pines recovered from Lake Louise, southern Georgia record climate conditions during a portion of the Little Ice Age (1580–1650) for the southeastern U.S. Oxygen isotope compositions for this time period are very similar to modern values (1895–1997) for this area. These results support previous studies that suggest the southeastern U.S. did not experience

dramatic climate effects of the Little Ice Age. The slight overall enrichment of oxygen isotope ratios may primarily reflect changes in precipitation source and moisture stress. The results suggest that tropical cyclone activity was low to moderate for 1580-1640, but increased noticeably in the last decade of the study (1640s).

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Chapter I. Introduction

Hurricanes are among the most devastating natural disasters, with extensive damage and loss of life brought by the accompanying ocean storm surges, flash flooding and high winds. They are the costliest natural disasters in the United States, costing on average more than $5 billion per year (Pielke and Landsea, 1998). An increased understanding of hurricane frequency and intensity would assist public planning at local and federal level and provide guidance to the insurance industry. Population increases along the Atlantic and Gulf coasts, increased wealth and the very high costs of repairing damage to public and business infrastructure damage adds to the urgency of improving our ability to monitor meteorological conditions conducive to spawning hurricanes and to model their development and course. A refined, long-term record of hurricane activity is needed. Longer-term records of hurricane activity dramatically enhance statistical long-range forecasts of cyclonic activity. A better understanding of the natural variability of hurricane frequency over several centuries is vital to our ability to understand and predict hurricane activity and will help to determine if there are specific actions we can take to mitigate potential increases in hurricane frequency.

Hurricane activity in the Atlantic Ocean is on the rise (*i.e*. Goldenberg *et al*., 2001; Elsner *et al*., 2000; Landsea *et al*., 1998). Some researchers have speculated the increase in hurricane activity may be largely influenced by the anthropogenic effects of global warming and greenhouse gases (*e.g*., Houghton, *et al*., 1996; Begley, 1996). Other researchers view this as unwarranted speculation. Atlantic hurricane activity exhibits distinct multidecadal cycles (*e.g*., Goldenberg *et al*., 2001; Elsner *et al*., 2000; Landsea *et al*., 1998). Thus, the current "active" hurricane period (1995-present) may only appear

more active than usual due to (1) better observation and tracking techniques within the recent decades using satellite imagery or (2) the lack of a longer record of hurricane history to compare with recent activity. Although certain systematic records of tropical cyclones extend to 1886 (Neumann *et al.*, 1993), systematic instrumental records of local meteorology extend only to 1940s. The relatively short record of instrumental observations creates difficulty for discerning long-term (multidecadal) trends and fluctuations in tropical cyclone activity or to differentiate natural versus anthropogenic components of these trends. Historical documentation provides exactly-datable daily if not hourly records of tropical cyclone events. South Carolina has an extensive archive of weather records through newspapers, diaries, etc., allowing detailed reconstruction of tropical cyclone activity back to mid-1700s (Mock *et al*. 2004). Rappaport and Fernandez-Partagas (1995) compiled a database of the deadliest tropical cyclone activity for the Atlantic basin from historical documentations dating back to 1492. Shiplogs, diaries, newspapers, and other documents provide valuable pieces to the puzzle of tropical cyclone reconstruction including intensity and track path. Although significant, historical documents are by nature limited to time, space, and circumstance. Tree-ring oxygen provide the advantages of being stationary and extending back hundreds to thousands of years, well beyond historical documents. Oxygen isotopes will also allow evaluation of longer-term climate factors that affect tropical cyclone frequency, which will be addressed in later sections.

Stable isotopes from several proxy sources have been examined to investigate climate change. For example, stable oxygen isotopes have been studied from polar/alpine (Dansgaard et al. 1969) and tropical ice cores (i.e., Thompson et al. 1995), coral (*i.e*.,

Swart *et al*., 1996), sagittal otoliths (*i.e*., Wurster and Patterson, 2001), sediment cores (i.e., Collins *et al*., 1999), speleothems (*i.e*., Musgrove, *et al*., 2001), and tree rings (*i.e*., Leavitt, 1987) for climate reconstruction. Tree rings provide a uniquely high resolution and precisely dated record of climate change, especially precipitation, which can be extended back for thousands of years (Fritts, 1976; Fritts and Swetnam, 1989; Switsur and Waterhouse, 1998). The oxygen isotopic compositions of tree rings may provide detailed insight into intraseasonal variation within the hydrologic cycle by examination of cellulose developed during intra-annual earlywood and latewood growing seasons. Isotopic variation with climate changes can be tracked on a century to millennial scale, with yearly-, seasonal-, or even higher-scale resolution using tree rings. This resolution has important implications for reconstructing major storm occurrences, such as hurricanes (Lawrence, 1998), as well as decadal to multidecadal climate oscillations, such as the Pacific Decadal Oscillation (D'Arrigo *et al*, 2001), that may influence the occurrence of hurricanes, moisture stress, and other climate events.

Chapter II. Background and Theory

2.1 Tropical Cyclones: Formation, Isotopic Systematics, and Controlling Climate Modes

2.1.1 Stable Oxygen Isotopes of Precipitation

Spatially and temporally, the stable isotope compositions of precipitation provide a snapshot of climate and atmospheric circulation. The wide geographic distribution of oxygen isotope variations in precipitation is related to many environmental factors. Latitude, altitude, distance to the ocean, the amount of rainfall, and the surface air temperature all have important effects on the isotopic signature of precipitation (Dansgaard 1964). Decreases in the isotopic values of precipitation along a latitudinal gradient result from cooling and distillation processes during transport of water vapor from low-latitudes to the poles (Dansgaard, 1964; Bowen and Wilkinson 2002). The isotopic composition of precipitation decreases almost linearly with altitude (except in the Himalayas and areas >5000ft) (Poage and Chamberlain 2001). This altitude effect is predominantly a result of Rayleigh distillation processes caused by orographic lifting and cooling of air masses and the resultant rainout of moisture (Dansgaard 1964). The continentality effect, or distance from the ocean, involves continual depletion of ^{18}O during water vapor transport and gradual condensation and rainout as moisture sources make their trajectories over land (Rozanski et al. 1992; Vuille et al. 2003). The $\delta^{18}O$ of precipitation over mid- and high latitude regions has been shown to positively correlate closely with long-term changes in surface air temperature (Rozanski et al. 1992). Within the tropics, rainy seasons and high temperatures generally coincide, and an amount effect on isotopic compositions is more prominent (Vuille et al. 2003). The isotopic composition of precipitation from a rain event also depends on the meteoric history of the

air mass and the type of cloud producing the precipitation (i.e. convective clouds produce precipitation with heavier $\delta^{18}O$ values than stratiform cloud; Hoefs 1997). Condensation processes result in large fractionations in ^{18}O between atmospheric water vapor and condensate. The oxygen isotope range of water vapor and precipitation near sea level is +5 to -50‰ (Dansgaard 1964; Lawrence and White 1991; note that typically the range of compositions is much more limited in a geographically limited area) while the $\delta^{18}O$ of surface waters of the open oceans only range from ~-0.5 to +1.5‰ (Bigg and Rohling 2000).

Oxygen isotopes undergo fractionations dependent on temperature and relative humidity. Oxygen isotopes of precipitation are measured against standard mean ocean water (SMOW), where the abundance ratio of $^{18}O/^{16}O$ in SMOW is 0.0020052 (Hoefs 1997). The fractionation factor ($\alpha_{liquid\text{-}vapor}$) for oxygen under equilibrium conditions (relative humidity 100%) increases from 1.00937 to 1.0117 as temperature decreases from 25˚C to 0˚C (Majoube 1971). As saturated air rises and cools, the isotopic composition of water vapor and condensate decrease due to the continual fractionation of ^{18}O from water vapor as the result of condensation and removal of the liquid water from the system, leaving the remaining vapor increasingly ^{18}O depleted (Hoefs 1997). Thicker clouds accentuate this phenomenon and oxygen isotope ratios in these clouds are even lower (Lawrence and Gedzelman 1996). Heavy isotopes are also continually removed from ambient vapor by diffusive vapor-liquid exchange of oxygen isotopes during precipitation events (Miyake et al. 1968). As a result, isotope ratios are lower both within and downwind of areas of organized precipitation (Gedzelman and Lawrence 1990).

Sublimation processes in cloud dynamics have a larger fractionation factor, $\alpha_{vapor\text{-}ice}$=1.0152 (0˚C) (Arnason 1969; Gat 1996) and storms associated with ice formation can also yield precipitation that is significantly ^{18}O depleted.

2.1.2 Tropical Cyclone Formation

Tropical cyclones are low-pressure systems that in the northern hemisphere rotate counterclockwise. Tropical cyclones affecting the North Atlantic Ocean form from pre-existing disturbances that generally emerge off the coast of Africa every three to four days beginning mid-summer as masses of unsettled weather. Tropical cyclones may also form from upper-level lows or along the trailing edge of cold fronts. Tropical storms that result from or are strengthened by baroclinic dynamics are termed baroclinically-enhanced or baroclinically-initiated tropical storms (Elsner and Kara, 1999). Tropical depressions possess winds of >62km/hr. They become tropical storms when winds reach between 63-118km/hr. Eventually, hurricanes develop from tropical storms with winds exceeding or equal to 119km/hr. The intensity and strength of a hurricane is measured using the Saffir/Simpson Hurricane Scale that consists of 5 categories (Table 1) (http://www.nhc.noaa.gov, 2002).

Tropical cyclone development requires three basic conditions. First, a pre-existing disturbance must exist, such as a thunderstorm. Second, ocean temperatures must be ≥26.5 ˚C to a depth of ~46 m. Warmer sea surface temperatures (SSTs) lower atmospheric stability allowing a greater depth of vortex penetration creating more cyclone stability and resistance to vertical wind shear. The local SST directly influences the strength of the tropical cyclone by providing moisture and latent heat; tropical storms are fueled by the transfer of latent heat and moisture from the oceans. Assuming constant

Table 1. Saffir-Simpson scale defining hurricane intensity.

Category	Wind Speed	Damage Effect
1	119-153 km/hr (74-95 mph)	Storm surge generally 1.2 - 1.5m above normal. No relavent structural damage to buildings. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Some coastal flooding and minor pier damage
2	154-177 km/hr (96-110mph)	Storm surge 1.8-2.4m above normal. Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2-4 hrs before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.
3	178-209 km/hr (96-110 mph)	Some structural damage to small residences and utility buildings, with a minoramount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris.
4	210-249 km/hr (131-155 mph)	More extensive curtainwall failures with some complete roof structure failure on small residences. Major erosion of beach areas. Terrain may be flooded well inland.
5	249+ km/hr (155+ mph)	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Flooding causes major damage to lower floors of all structures near the shoreline. Massive evacuation of residential areas may be required.

relative humidity, the latent heat content of the air increases exponentially with increases in SSTs, as indicated by the Clausius-Clapeyron relation: $(d\ln p)/(dT)=(\Delta H_{vap})/(RT^2)$, where p is water vapor pressure, T is temperature (Kelvin), ΔH_{vap} is molar enthalpy of vaporization of water, and R is the ideal gas constant (8.3145 J/mol•K). Tropical cyclone development and intensification are most sensitive to small increases in SST between 26-29°C (Emanuel, 1991; DeMaria and Kaplan, 1994; Holland, 1997). Within the Atlantic basin, this temperature interval corresponds with the ability of cumulus clouds to begin penetrating the trade wind inversion at 1-2 km altitude (Emanuel, 1986). This penetration leads to initial deep convection and development of a warm core above 10km altitude (Holland, 1997). Above-normal SSTs, in concert with below normal sea level pressure (SLP), results in weaker trade winds and reduced vertical shear, and leads to greater hurricane potential (Landsea *et al*., 1998). Eighty-five percent of Atlantic storms form during the warm months of August through October (Shapiro, 1987).

The third condition for tropical cyclone development is a low magnitude of vertical shear of horizontal wind between the upper (~200mb) and lower (~850mb) troposphere. According to Gray (1968), the major inhibiting factor for tropical cyclone development is tropospheric vertical wind shear (VWS). Strong VWS prevents asymmetric organization of deep convection, inhibiting initiation and/or growth of tropical cyclones (Knaff, 1997). Tropical cyclone intensification is inhibited when VWS values exceed 30.6km/hr (8.5m/s), and tropical cyclone initiation is prevented at VWS values exceeding 36km/hr (10m/s) (Zher, 1992; Fitzpatrick, 1995). Thus, VWS and SSTs are the primary factors regulating tropical cyclone intensification (DeMaria *et al*., 1993).

The three main structures of a hurricane, the rain bands, the eyewall, and the eye, typically stretch ~300 miles across (Fig. 1). The rain bands of a hurricane can extend for tens to hundreds of kilometers as a dense band of thunderstorms that slowly spiral in a counterclockwise direction. Tropical cyclone precipitation is asymmetrically distributed about the eye and is influenced by windshear, sea surface temperatures, moisture distribution, storm intensity, storm location, and storm translation speed (Lonfat, et al., 2004). The eyewall is a dense wall of thunderstorms that contain the strongest winds of the storm. The eye of a hurricane is the cloudless calm center usually 30 to 65 kilometers across. The eye forms as rapidly sinking air dries and warms the center of the hurricane. Maximum rainfall is associated with the front quadrant of the tropical cyclones relative to its forward motion and has the most intense and strongest winds due to the effects of advection and the larger atmospheric flow (or its steering winds) (http://www.noaa.gov, 2002). Tropical storms tend to have the most intense rainfall in the front-left quadrant while major hurricanes exhibit maximum rainfall in the front-right quadrant of the storm system relative to its direction of motion (Lonfat et al. 2004).

2.1.3 Oxygen Isotope Systematics of Tropical Cyclone Systems

Tropical cyclones are dynamic mesoscale convective systems whose extreme precipitation efficiency may permit the weather phenomenon to be traced isotopically in proxies through geologic time. Tropical cyclones produce precipitation with distinctly lower $\delta^{18}O$ values (< -6‰) than other tropical rain systems (~ -6 to 0‰) (Dansgaard 1964; Nicolini et al. 1989; Lawrence and White 1991). Two basic physical factors govern $\delta^{18}O$ values in precipitation and meteoric water vapor: (1) Isotopic fractionation during condensation, where ^{18}O is preferentially incorporated into the more condensed

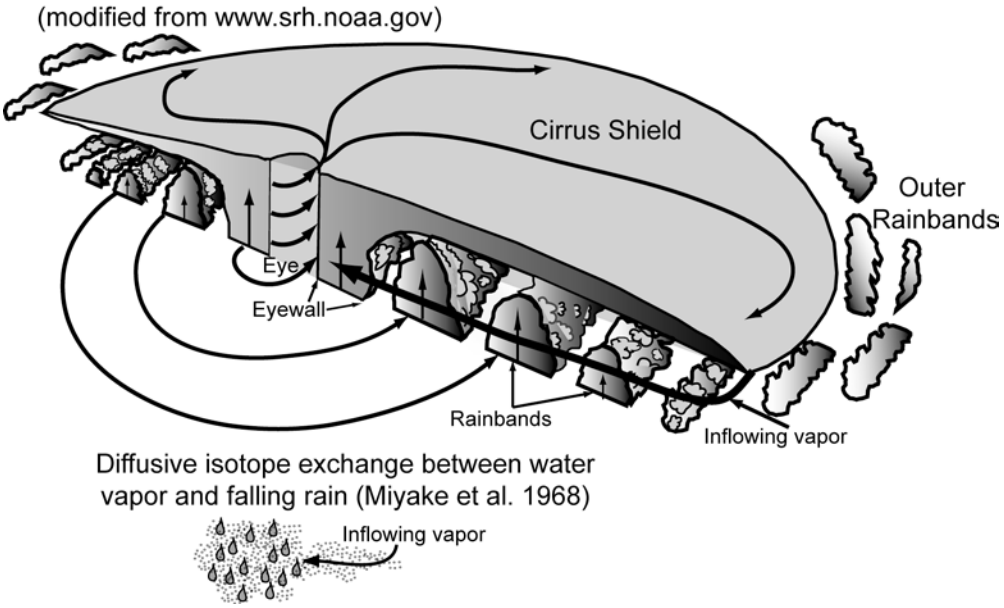

Figure 1. Structure of a tropical cyclone. Diffusive isotopic exchange occurs between oxygen isotopes of the water vapor and falling rain; therefore, isotopic depletion increases inward from the outer rainbands toward the eye.

phase; (2) Diffusive isotopic exchange between falling rain and ambient vapor, which result in a ^{18}O enrichment of the falling rain and a decrease in vapor compositions. Over time, this process lowers the isotope ratio of ambient vapor near the surface and results in a temporal decrease in isotope ratios of precipitation during storm events (Miyake et al., 1968; Lawrence and Gedzelman 1996; Gedzelman et al., 2003) (Fig.1). Large, organized, and long-lived storms, such as tropical cyclones, particularly amplify these isotope effects. The oxygen isotope ratio of water vapor and condensate sharply decreases with cloud height (Dansgaard, 1953; Ehhalt and Östlund 1970). In relatively long-lived storm systems such as tropical cyclones, the total mass of rain produced far outweighs the mass of vapor in the storm at any given moment, and the high condensation efficiency and great cloud height may result in $\delta^{18}O$ values of precipitation that approach the $\delta^{18}O$ of the source water vapor (Lawrence and Gedzelman, 1996). Within the tropical cyclone, oxygen isotope depletion increases radially towards the eye. Lofting of rain or sea surface spray during strong updrafts may enrich water vapor in the eyewall, replenishing ^{18}O isotopes deep within the cyclone (Gedzelman et al. 2003). Gedzelman et al. (2003) hypothesize that tropical system rains can develop low isotope ratios within 24 to 48 hours after organized secondary circulation occurs, long preceding hurricane strength status. The extent of ^{18}O depletion in tropical cyclone precipitation is not a measure of the strength of the storm, but rather a possible indicator of circulation intensity. According to the model of Gedzelman et al. (2003), initial intensification of a tropical cyclone involves preferential incorporation of ^{16}O in snow that is thrust into the upper troposphere. This snow is temporally isolated from the water vapor pool available for precipitation, creating a pulse of isotopically enriched precipitation. Over time, this snow is flushed downward

resulting in an abrupt depletion in precipitation. Efficient recycling of water, with diffusive isotopic exchange between inflowing vapor and falling rain in rain bands, leads to inward decrease of ratios towards the eye. Low ratios of oxygen isotopes have still been observed near the outer fringe (Lawrence et al., 2002).

2.1.4 Tropical Cyclones and Climatology

Greater than 85% of major hurricanes in the tropical Atlantic Ocean and Caribbean Sea propagate westward from Africa between 10˚ and 20˚N and 20˚ to 60˚ W (Goldenberg and Shapiro, 1996). This latitudinal belt of atmospheric African waves, which develop into tropical depressions, is termed the main development region (MDR). Due to high vertical wind shear (>28.8km/hr), the entirety of the Atlantic Basin is not very conducive to tropical cyclone formation. The tropical North Atlantic Basin (including the Caribbean Sea and Gulf of Mexico) has both warm SSTs and low vertical wind shear, especially during the months of August, September and October. These factors create favorable conditions for tropical cyclone formation and, indeed, correspond to the main three months of hurricane formation (Landsea, 1993; Shapiro and Goldenberg, 1998). Hurricanes may survive more than two weeks over the ocean.

Tropical cyclone development varies dramatically on both annual and decadal scales, despite the relatively stable influx of African waves in the tropical Atlantic (Avila *et al*., 2000). This variation is caused by changes in both local and remote climate forcing factors within the MDR. Within the tropical Atlantic, five local influencing factors are:

- lower stratospheric Quasi-Biennial Oscillation (QBO),
- sea-level pressure (SLP),

- precipitation in Africa's western Sahel,
- SSTs, and
- vertical shear of the horizontal environmental wind (VWS).

The most important factors are SSTs and VWS, which have been previously addressed. The important remote factors are the effects of El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), Madden-Julian Oscillation (MJO) (in the Gulf of Mexico), Atlantic Multidecadal Oscillation (AMO) and changes in solar intensity.

The lower stratospheric Quasi-Biennial Oscillation (QBO) is an east-west oscillation of stratospheric winds that encompasses the earth near the equator (Wallace, 1973). The QBO oscillation is asymmetric, with the west phase active at 30mb for ~13-16 months followed by a slow transition to the east phase for ~12-15 months. Because easterly winds uniformly dominate the lower stratosphere over the MDR during the hurricane season (ASO), the QBO west phase often expresses itself as weak easterly winds at 30 to 50mb and enhances increased hurricane activity. Hurricane activity is 50-100% higher in the North Atlantic Basin when the QBO is from the west as opposed to the east (Gray 1984a). If the QBO is in the east phase during the hurricane season, then strong easterly winds (20-30m/s) result in decreased hurricane activity (Gray, 1984a; Shapiro, 1989; Gray *et al*., 1992). One argument of the QBO mechanisms relates to vertically propagating waves that transfer momentum upward from the troposphere into the stratosphere (Lindzen and Holton, 1968). This upward propagation may lead to increased vertical shear of the horizontal winds blowing largely from east to west, which

in turn disrupts tropical cyclone formation by tearing apart their vertical structure (Gray *et al*., 1993).

In general, below normal sea level pressure (SLP) is associated with more active Atlantic hurricane seasons while above normal SLP are typically associated with less active seasons (Shapiro, 1982; Gray, 1984b; Knaff, 1997). Below normal SLP within the MDR works in combination with near normal pressures within 10° of the equator, effectively loosening the meridional pressure gradient, thereby weakening the easterly trade winds and contributing to decreased vertical shear. Low SLP within the MDR reflects a poleward shift and/or strengthening of the intertropical convergence zone (ITCZ). This shift and/or strengthening of the ITCZ decreases drying in the MDR, allowing more available moisture to fuel cyclonic activity. In contrast, above normal SLP in the MDR in combination with near normal pressures within 10° of the equator effectively tightens the meridional pressure gradient, strengthening the easterly trade winds and resulting in increased vertical shear winds that inhibit hurricane activity (Gray *et al*., 1993, 1994).

For the last century, precipitation in Africa's western Sahel (June-September) has exhibited a strong correlation with Atlantic hurricane activity, especially intense hurricane activity (Reed, 1988; Landsea *et al*., 1998). Wet years within the Sahel correspond to an increase in intense hurricane activity, with an opposite effect in dry years. Atlantic hurricane activity and moisture conditions within the Sahel are possibly connected by (1) variation in tropospheric vertical shear and (2) African easterly wave intensity (Gray, 1990; Gray and Landsea, 1992; Shapiro and Goldenberg, 1998). Easterly waves are convectively active troughs in the lower troposphere which track westward

across the Atlantic in the trade wind flow between 10° and 20°N (Saunders and Harris, 1997). Despite the strong association of Atlantic major hurricanes with increased precipitation in the western Sahel of Africa, major hurricanes affecting the Gulf Coast exhibit little relationship to fluctuations in West African rainfall (Gray and Landsea, 1992; Landsea *et al.,* 1992). This association may be due to the larger number of systems originating from noneasterly wave systems affecting the Gulf (Goldenberg and Shapiro, 1996).

Other climate factors thought to influence the Atlantic hurricane activity are ENSO, PDO, NAO, MJO, AMO, and changes in solar intensity. ENSO fluctuates on 3-5 year time cycles in the ocean-atmospheric system throughout the tropical Pacific (Philander 1989). El Niño years cause anomalous warm waters to develop off the South American tropical West Coast and in the equatorial central Pacific. El Niño activity creates extra deep cumulus convection within the eastern Pacific. This enhanced convection results in anomalously strong westerly upper tropospheric wind patterns over the Caribbean and equatorial Atlantic which effectively reduces the occurrence of hurricanes in the North Atlantic basin (Gray, 1984). Hurricane activity returns to normal in the second season following an El Niño event. La Niña events create cold SST anomalies in the eastern and central Pacific, which aid in decreasing 200mb westerlies and vertical wind shear, and therefore enhance hurricane activity (Landsea *et al*. 1998).

In addition to affecting hurricane activity for the Atlantic basin, ENSO conditions may also result in precipitation changes over southern Georgia prior to and during the growing season. Precipitation from the Pacific may be carried (via storms) to the Atlantic coast depending on the strength, intensity, and duration of the El Niño episode

(Boyles and Raman, 2003; Gershunov and Barnett, 1998). Precipitation increases are observed in winter during El Niño events and decreases during La Niña events (Roswintiarti et al. 1998). During the past 48 (1949–1997) years, the five strongest El Niño events occurred in 1982/1983, 1997/1998, 1957/1958, 1986/1987, and 1972/1973 (Hare and Mantua, 2001) and the five strongest La Niñas years are 1973–1974, 1954–1956, 1964–1966, 1988-1990, and 1949–1951 (Wolter and Timlin 1993, 1998).

The MJO primarily affects hurricane occurrence and activity in the Gulf of Mexico and the western Caribbean Sea. Operating on an intraseasonal interval of 30 to 60 days, this oscillation is characterized by an episodic modulation of tropical convection and winds that propagate eastward from the Indian Ocean toward the Pacific Ocean (Madden and Julian, 1994; Hendon and Salby, 1994). The MJO results in alternating episodes of westerly and easterly wind anomalies (especially 850mb winds) over the eastern Pacific. Tropical cyclone genesis and activity in the Gulf of Mexico and Caribbean Sea are greatly encouraged when MJO winds are westerly. MJO events are stronger and precipitation is enhanced during neutral El Niño or weak La Niña years (Maloney and Hartmann, 2000; http://www.cpc.ncep.noaa.gov, 2004).

The NAO is a quasi-decadal oscillation between two atmospheric mass centers: the Icelandic low (Stykkisholmur, Iceland) and the Azores high (Lisbon, Portugal) pressure systems. A positive (negative) NAO index occurs when the pressure over the subtropics is higher (lower) than normal and pressure over the higher latitudes is lower (higher) than normal. A positive (negative) NAO index is associated with warmer temperatures over the eastern United States and stronger (weaker) westerlies and northeast trade winds (Hurrell, 1995, 1996; Boyles and Raman, 2003). Major hurricane

activity in the Atlantic/Caribbean/Gulf of Mexico basins appears to be closely connected to the strength and phase of the NAO. Periods of negative NAO activity correspond with greater major hurricane activity while positive NAO periods relate to less major hurricane activity. The position of the Azores (subtropical) high influences the strength of trade winds across the tropical Atlantic and Caribbean basin. During positive NAO phases, the Azores high is shifted southwestward closer to the Caribbean Sea. As a result, SSTs are lower in the MDR and the trade winds across the MDR are relaxed creating more intense westerlies from a monsoon trough or a favorable phase of the MJO (Cayan, 1992; Elsner *et al*., 2000a). The NAO also influences where major hurricanes tend to track. During positive NAO years, major hurricanes more commonly strike the east coast. During negative NAO years, major hurricanes more often strike the Gulf Coast region (Elsner et al. 2000b; Molinari and Mestas-Nuñez, 2003).

The PDO is an index of decadal, oscillatory periods of atmospheric-oceanic variability expressed as dominant modes of North Pacific sea surface temperatures (SST) (D'Arrigo *et al*. 2001). For the 20th century, PDO fluctuations occur with periodicities of 15-25 years and 50-70 years (Minobe 1997). The positive or warm phase of the PDO is characterized by anomalously cool SSTs in the interior North Pacific, anomalously warm SSTs along the Pacific coast, and below average SLP over the North Pacific. The negative or cool phase of the PDO is exemplified by anomalously warm interior North Pacific SSTs, anomalously cool SSTs along the Pacific coast, and above average SLP over the North Pacific (Mantua and Hare, 2002). Warm/positive PDO regimes have been identified for the periods 1925–1946 and 1977 to the mid 1990's where the PDO is currently believed to be switching to a cool/negative phase. Cool/negative regimes

occurred in 1890–1924 and 1947–1976 (Mantua et al., 1997; Minobe 1997). Tree-ring studies have suggested that the strength and punctuation of the PDO has changed over time. Prior to the mid-1800s, PDO variability was apparently more strongly expressed compared to the last 1.5 centuries (D'Arrigo *et al*., 2001; Bondi *et al***.**, 2001).

The PDO is a large climate phenomenon with far reaching effects into the equatorial Pacific basin as well as the Atlantic Ocean and Gulf of Mexico, and thus affecting climate variability in the United States. ENSO events in the equatorial Pacific may be strengthened by the PDO. ENSO events are stronger and more likely to occur when the ENSO phase is coincident with the respective PDO phase, i.e., El Niño and warm/positive PDO; La Niña and cool/negative PDO (Gershunov and Barnett, 1998). The PDO has been linked to summer rainfall and moisture stress variability in the U.S. (Nigam *et al*., 1999). Climate conditions in the southeastern U.S. are largely affected by the PDO, especially the winter and spring seasons. The warm PDO phase relates to wet conditions for the southeastern U.S., and cool PDO phase relates to warm dry conditions (Mantua and Hare, 2002). Analysis of climate trends in North Carolina (1949–1998) reveals that precipitation patterns correlate well with the phases of the PDO while temperature patterns correlate better with phases of the NAO for this region of the eastern U.S. seaboard (Boyles and Raman, 2003).

The AMO is the leading mode of low frequency sea surface temperature variability in the North Atlantic basin (0-70˚N), fluctuating over a 0.4˚C range (Kerr, 2000). This SST fluctuation is believed to result from internal ocean-atmosphere variability associated with the intensity of the Atlantic thermohaline circulation and associated meridional heat transport (Collins and Sinha, 2003; Delworth and Mann,

2000). Over the measured record (1856-Present), a 65–80 year cycle is observed with warm periods existing 1860–1880 and 1940–1960 and cool periods occurring 1905–1925 and 1970–1990 (Enfield *et al*. 2001). The AMO is currently thought to be shifting into a warm phase. Similar oscillations at 60–110 year intervals are observed in paleoclimate data from North Atlantic climate reconstructions dating back to 1650 A.D. (Delworth and Mann, 2000). The AMO is linked to multi-year precipitation anomalies over North America (Enfield *et al*. 2001; McCabe *et al*. 2004). During warm (cool) phase of the AMO, the 500hPa geopotential height decreases (increases) across the southeastern U.S. resulting in increased (decreased) winter cyclonic activity and rainfall (Kalnay *et al*. 1996). The AMO is also believed to effect Atlantic hurricane formation directly and indirectly by modulating the strength of El Niño events and African moisture stress frequency (Folland *et al*. 1986).

Low frequency changes in solar activity have been speculated to influence North Atlantic hurricane frequency and/or intensity. Changes in solar activity are tracked through sunspot cycles (11 year and 22 year solar cycles) and/or the Saros lunar cycle (18–19 years). Only those hurricanes which are baroclinically initiated or baroclinically enhanced appear to be notably affected by low frequency changes in solar activity. Increases in solar activity are hypothesized to increase evaporation at the ocean surface. This surface ocean warming may lead to increased evaporative latent heat transport and consequently atmospheric instability, conditions more conducive for hurricane formation. Increased solar activity may also lead to enhanced hurricane intensification by providing extra ionization of the upper extent of the hurricane vortex. This extra ionization results in additional latent heat release that leads to warming of the storm core (Tinsley, 2000).

Tropical only hurricanes form at latitudes where conditions are already near water vapor saturation and are less sensitive to slight increases in latent heat fluxes (Elsner and Kara, 1999).

2.2. Tree Rings and Oxygen Isotopes

The oxygen isotope composition of α-cellulose in trees is predominately related to precipitation, temperature, and relative humidity (Saurer, *et al*., 1997a; Lipp *et al*., 1996; Epstein et al., 1977). Temperature exerts an important control during fractionation of the source water, and is important for determining evaporation rates in soil water. However, there is little or no temperature dependence of the net biological fractionation in tree rings (Roden and Ehleringer, 2000). The influence of relative humidity is still uncertain. Studies by Roden et al. (2000, 2002) show that humidity signals may or may not observed in oxygen isotopes of cellulose depending on extent of nonexchangeable oxygens derived from stored reserves.

Four major factors are considered to control the ^{18}O signal in tree: **(**Fig. 2):

- The isotopic composition of water utilized in the production of cellulose: soil water and precipitation (Saurer *et al*., 2000) (I; refer to Fig. 2);
- Isotopic enrichment of leaf-water due to the evaporative effects of stomatal transpiration (Dongman *et al*., 1974) (II);
- The biological fractionation occurring between cellulose and source water (DeNiro and Epstein, 1979; Sternberg *et al*., 1986) (III); and

Exchange between xylem water and sucrose oxygen during transfer of sucrose produced in leaves to the site of cellulose production (Hill *et al*., 1995; Farquhar *et al*., 1998). This process, in turn, dampens (reduces) the effect of leaf-water enrichment (Saurer *et al*.,

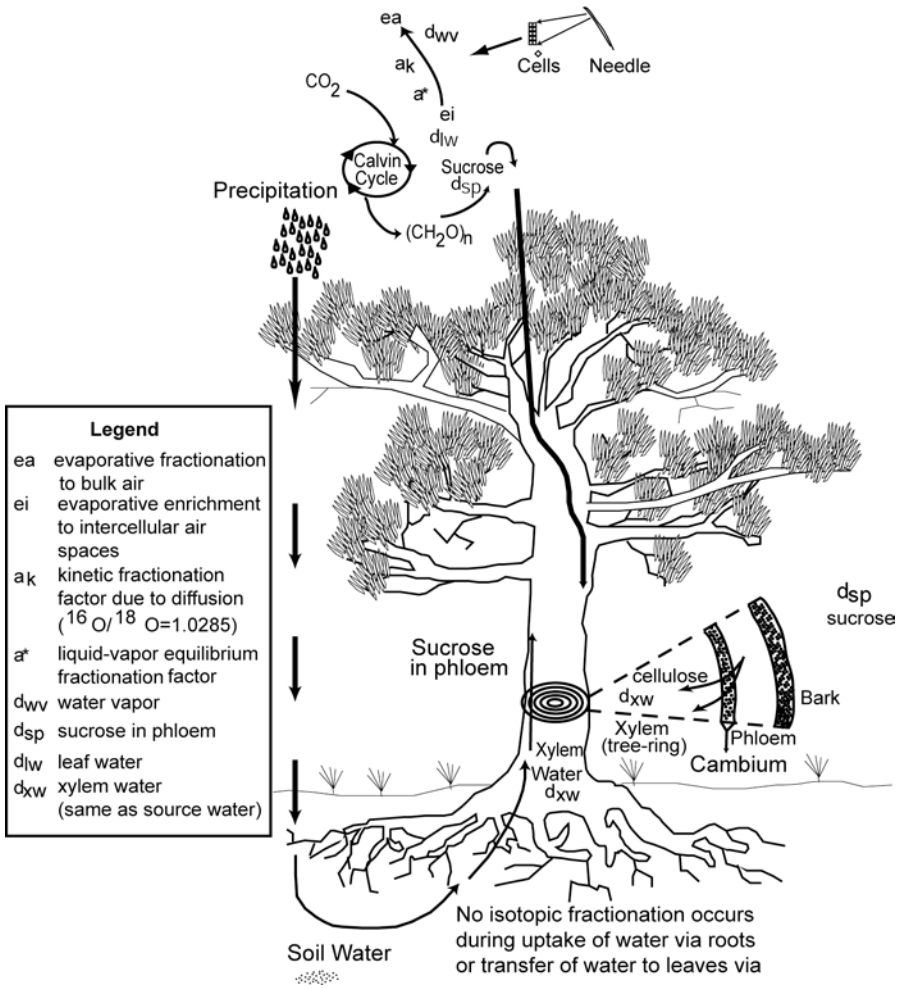

Figure 2. Major processes controlling the ^{18}O signature in tree rings for pines.

1997b) (IV). The isotopic composition of soil water is derived from the source precipitation, but it is subsequently modified (isotopically enriched) by evaporation or localized inhomogeneities in the soil. These effects are relatively minor in humid, warm-temperate regions. The admixture of isotopically-distinct (and generally heavier) groundwater with soil water may also modify soil water compositions where the water table penetrates into the vadose zone. The shallow root systems of the conifers (*Pinus palustris* Mill. and *Pinus elliottii* Engelm.) used in this study minimize the uptake of groundwater relative to vadose zone, soil water. Isotopic fractionation does not occur during the uptake of soil water via the roots or during the transfer of water to the leaves via the xylem (Forstel and Hutzen, 1983).

Other sources of oxygen isotopic fractionation in α-cellulose include enrichment of leaf-water due to evaporative effects of stomatal transpiration. This enrichment occurs as water vapor diffuses into the boundary layer between the leaf water and the free atmosphere and is related to relative humidity, under steady state conditions. Dongman *et al*. (1974) modeled this relationship (later modified by Aucour *et al*., 1996) to calculate the oxygen isotopic composition of leaf water and cellulose:

$$(1)\ \delta^{18}O_{\text{leaf water}} = (1 - f)\,[\alpha^{*} + \alpha_k\,(1 - h) + h\delta_{wv} + (1 - h)\,\delta_{sw}] + f\delta_{sw}$$

$$(2)\ \delta^{18}O_{\text{cellulose}} = \delta^{18}O_{\text{leaf water}} + \alpha_{biochem}$$

where f is the fraction of leaf water not subject to evaporation (Allison *et al*., 1985) and the term which accounts for the modification of photosynthate isotopic composition due to exchange of stem water prior to cellulose formation (Saurer *et al*., 1997a), α^{*} is the liquid-water equilibrium fractionation for water (Majoube, 1971), α_k is the kinetic liquid-

vapor fractionation of water which is affected by the leaf boundary layer airflow dynamics (Buhay *et al*., 1996), *h* is the relative humidity, δ_{sw} is the isotopic composition of the source water, δ_{wv} is the isotopic composition of the water vapor, and $\alpha_{biochem}$ is the biological fractionation factor due to carbonyl-water interactions during biosynthesis (27± 3‰; DeNiro and Epstein, 1979, 1981; Sternberg, 1989). Relating Eqns. (1) and (2) in terms of $\delta^{18}O_{cellulose}$ results in Eqn. (3):

$$(3)\quad \delta^{18}O_{cellulose} = (1 - f)\,[\alpha* + \alpha_k\,(1 - h) + h\delta_{wv} + (1 - h)\delta_{sw}] + f\delta_{sw} + \alpha_{biochem.}$$

The isotopic influence of leaf water transferred to tree ring cellulose is dampened by several factors. First, leaf water is compartmentalized so that not all leaf water is subject to the effects of evaporation. Second, leaf water is an inhomogenous mixture of three isotopically different sources: evaporating surfaces, chloroplasts, and vein fractions. Water used in cellulose synthesis is the same water the chloroplast utilizes for photosynthesis, and it is generally ^{18}O-depleted relative to water at the evaporating surfaces (Yakir *et al*., 1994). Theoretical and experimental evidence suggests ≤ 45% of the leaf water's ^{18}O signal, transferred to sucrose manufactured in the chloroplasts, is exchangeable with stem water prior to cellulose synthesis (DeNiro and Cooper, 1989; Sternburg *et al*., 1986; Hill *et al*., 1995; Farquhar *et al*., 1998), further reducing the leaf water's isotopic influence on the cellulose. The extent to which exchange with stem water occurs depends on many factors, including the tree species and its growth environment. The *f*, or dampening, factor must be well understood in order to use the oxygen isotope compositions directly as a measure of temperature or precipitation composition (Saurer *et al*., 1997a ; Anderson *et al*., 2002). For the application examined in this study, with its

focus on the *relative* directions and magnitudes of change from a normal trend of isotopic values, and for which the isotopic record is preserved in specimens of the same species from the same environment, the dampening factor need not be considered. It does not affect the time series record of relative isotopic changes.

Chapter III. Study Location

Longleaf (*Pinus paulstris*, Mill.) and slash (*Pinus elliottii*, Engelm.) pines from southern Georgia are utilized in this study. Several slash and longleaf pine trees were cut down on the Valdosta State University campus (30.84°N; 83.25°W) during the 1990s and sections of these trees have been archived for paleoclimate research. Subfossil longleaf wood from Lake Louise located in south-central Georgia (30.43°N; 83.15°W) was also collected (Fig. 3). Lake Louise is a 5.4ha humic lake that is 6m deep situated ~12km south of Valdosta. This location, heavily logged in the 19th century, contains tree stump specimens dating back to the 1400s. Previous climate reconstruction using tree-ring width analysis suggests a strong relationship to summer precipitation and proposes enhanced summer rainfall during periods: late 1500s, mid-1600s, late 1700s, and early 1900s, and diminished rainfall during periods: mid-1500s, early 1600s, late 1600s, early-mid 1800s, and late 1900s, with the majority of the 18th century being a quiescent period (Grissino-Mayer and Tepper, 2002). The modern average annual temperature is 20.3°C (69°F), and average annual precipitation is 112 cm (44 in). The general soil type on the Georgia Coastal Plain is well-drained loamy sand (Stevens 1979). The hurricane season for the study area extends from May 1st through October with highest intensities in August, September, and October. Appendix 1 contains monthly temperature and precipitation records from various weather stations at and near Valdosta mainly for the hurricane season months, especially August, September, and October. The average oxygen isotope value for precipitation collected at Georgia Station (33.18°N, 84.41°W) is –3.9‰ located in the southern coastal plain of Georgia, are situated to capture both Atlantic and Gulf

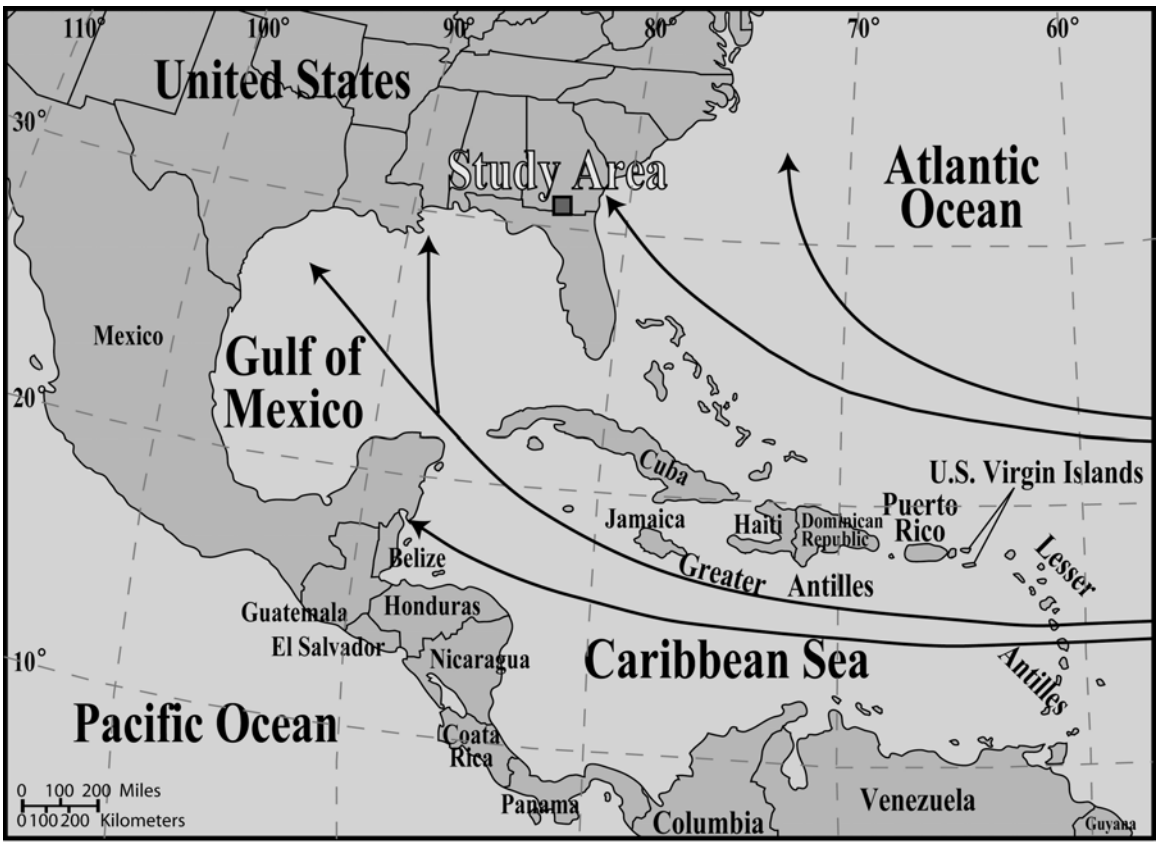

Figure 3. Map of study area showing proximity to Atlantic, Caribbean, and Gulf tropical cyclones. Generalized storm tracks are shown (http://rst.gsfc.nasa.gov).

coast tropical cyclones that impact the southeast. Although we may achieve an encompassing record of tropical cyclones influencing the area, the inability to differentiate paleocyclone impact from the southeast/Atlantic side or from the Gulf coast side hampers interpretation of the factors controlling tropical cyclone steering mechanisms. The tree-ring chronology at these sites was readily developed since both slash and longleaf pines lay down consistent annual rings.

Chapter IV. Methodology

4.1 Collection and Dating

Cross-section slabs of two pine tree species, *Pinus elliotii* Engelm. (1997–1960) (slash pine) and *Pinus palustris* Mill. (1975–1580) (longleaf pine) collected at the Valdosta State University campus and Lake Louise are utilized in this study. The slabs were sanded with corundum grit sandpaper to 400 mesh. Tree-ring widths were measured using a Leica StereoZoom4 binoc scope with a Velmex measuring stage connected to a Medir computer program interface. The tree rings were then statistically correlated and cross-dated using COFECHA (Stokes and Smiley, 1996; Grissino-Mayer, 2001).

4.2 Alpha-Cellulose Extraction: A Modified Extraction Technique for Resin-Rich Conifers

Most tree-ring oxygen isotope studies examine and analyze only the α-cellulose component of the wood. Alpha cellulose is the preferred constituent because whole wood and holocellulose contain mobile compounds (*i.e*. carbohydrates and starches) that can move across the ring boundaries, whereas α-cellulose is relatively immobile and forms *in situ* relative to the tree ring (Ramesh *et al.* 1985; Leavitt and Danzer, 1993; Switsur *et al.*1995). Therefore, α-cellulose does not contain mobile impurities unrelated to the climate and environment during cellulose growth.

The original techniques for α-cellulose extraction from whole-wood samples are well established and described by Green (1963). The technique used in this study employs modifications of that technique made by Loader *et al*. (1997). Longleaf pines in the Georgia area are highly resinous, and were historically tapped for turpentine

production (Grissino-Mayer *et al*. 2001). Published methodologies for α-cellulose extraction incompletely removed resins from some of the Georgia samples. The following methodology was developed to ensure complete resin removal.

Annual tree rings contain conspicuous components of early growth (spring to early summer, earlywood, EW) and late growth (late summer to fall, latewood, LW) (Fig. 4). Yearly segments of EW and LW are separated and cut into wood slivers (~40μm) with a razor blade. Resins are removed from the shavings using an Accelerated Solvent Extraction 300 (ASE 300) applying the following conditions: solvents (3:1) of toluene and reagent alcohol at 125˚C and 1500 psi (6 minutes) for 2 cycles (Table 2a). Next, samples are placed in separate extraction thimbles and placed in a beaker with DI water and acetic acid and $NaClO_2$ (Table 2b). Sample beaker(s) are placed in an ultrasonic water bath at 70˚C for four hours. Three more acetic acid and sodium chlorite additions are made after each hour. After the four hour acetic acid/sodium chlorite treatment, thimbles are removed, vacuum filtrated washing once with ~50ml of hot DI water followed by ~50ml of cold DI water.

At this point, the holocellulose should be white. If the samples are still tinged yellow or orange, then further acetic acid /sodium chlorite treatment is necessary. Once holocellulose is washed, the thimbles are placed in a clean beaker(s) with 10% (w/v) NaOH added. The wood shavings will turn brown if pine resins have not been completely removed. The samples are placed into a water bath at 80˚C for 45 minutes with ultrasonic agitation. Samples are then removed and vacuum filtrated with ~50ml of cold DI water. This step leaches carbohydrates such as mannan and xylan from the holocellulose. Once filtered, the samples are placed in a clean beaker(s) with 17% (w/v)

Figure 4. Sub-fossil wood from Lake Louise, southern Georgia (1850–1900). Each light (earlywood-EW) and dark (latewood-LW) band constitute one year of tree ring growth. Semi-annual resolution is obtained by sampling EW and LW separately; even higher resolution is sometimes possible.

Table 2. Accelerated Solvent Extraction (ASE) parameters are described in (a). Acidification reagents of acetic acid and sodium chlorite combine to bubble chlorine gas through the wood sample (b).

(a)

ASE 300 Parameters			
Heat	6 minutes	Temperature	125 °C
Static	10 minutes	Pressure	1500 psi
Flush % Volume	60	Solvents	
Purge	100 seconds	Toulene	70%
Cycles (#)	3	Reagent Alcohol	30%

(b)

Acidification Reagents	
Reagent	Weight/Volume (per 1 gram of sample)
Deionized Water	175 ml
Acetic Acid	1.7 ml
Sodium Chlorite ($NaClO_2$)	2.5 g

NaOH added and placed in an ultrasonic bath for 45 minutes at room temperature. The samples are then vacuum filtrated washed first with ~20ml of 17% NaOH followed with copious amounts of cold DI water and then washed with ~20ml of 1% (w/v) HCl. The samples are washed with copious amounts of DI water again until the rinse water is neutral. The α-cellulose is then dried in a vacuum oven at 40˚C for ~4 hours. All glassware is cleaned prior to use in a muffle furnace (550˚C for 1.5 hours).

To evaluate whether the modified extraction methodology caused isotopic fractionation or exchange with the α-cellulose, standard α-cellulose material (Sigma® α-cellulose) was subjected to all of the combinations of steps we found necessary to fully extract resin from sample material. The treated Sigma cellulose was then analyzed for oxygen isotope composition, using the mass spectrometric techniques described in the following section. The results are shown in Table 3 and demonstrate that our proposed methodology does not fractionate or alter the isotopic composition of the α-cellulose.

4.3 *TC/EA Mass Spectrometry*

Oxygen isotopes are analyzed using a quantitative high temperature carbon reduction elemental analyzer (TC/EA) interfaced with a continuous flow isotope ratio mass spectrometer (Finnigan MAT Delta Plus XL IRMS) at the University of Tennessee, Knoxville. Approximately 100μg (±30μg) of each sample are weighed and loaded into silver caps. The silver caps are placed into an auto sampler on the TC/EA where the samples are sequentially pyrolized in a graphite furnace (reactor), liberating organic oxygen to produce CO. The TC/EA oven is set at 100˚C and the graphite reactor oven at 1450˚C. The CO is carried in a He-stream to the mass spec for measurement of $^{18/16}O$ ratios. Four internal standards (SIRFER, Jahren, Chihuahua calcite (CHCC) and

Table 3. Isotopic composition of standard α-cellulose after extraction

Detailed extraction method used	**Average $\delta^{18}O$ α-cellulose (‰,V-SMOW)**
Sigma α-cellulose, untreated	27.34 (n= 6)
Sigma α-cellulose subjected to methodology outlined in text	27.15 (n=3)
Sigma α-cellulose subjected to methodology outlined in text, with 70°C water bath applied during 17% NaOH treatment	27.01 (n=3)
Sigma α-cellulose subjected to methodology outlined in text plus post-method treatment with acetic acid and $NaClO_2$ with heat (70°C) for 5 hours.	27.44 (n=3)

comercially produced Σ-cellulose ™) are used, as well as the NBS-19 carbonate standard(Table 4) (Appendix 1).

Table 4. Standards utilized in study involved three internal standards (SIRFER-cellulose, Jahren-cellulose, CHCC ((f)- carbonate) and one National Bureau of Standard- NBS (19) carbonate standard.

Correct Value	Standard	No.of Samples	Average Value	Standard Deviation
28.3	SIRFER	n=5	28.3	0.21
29.3	Jahren	n=5	29.3	0.17
21.4	CHCC (f)	n=4	21.4	0.26
28.6	NBS-19	n=18	28.6	0.36

Chapter V. A Tree-Ring Oxygen Isotope Record of Hurricanes and Moisture Stress

5.1 Abstract

Geological proxies are needed to extend the record of hurricane frequency beyond historical observations. Tree rings preserve uniquely high resolution and precisely dated records of past environmental conditions. We present a 227-year record of oxygen isotope compositions of alpha cellulose in slash and longleaf pine tree rings of the southeastern U.S. that preserves evidence of past tropical cyclone activity, seasonal droughts, and multidecadal climate oscillations. The results suggest the potential for a tree-ring oxygen isotope proxy record, extending back many centuries, of long-term trends in hurricane occurrence and the possible forcing factors that govern such variations.

5.2 Introduction

Hurricanes pose a potentially devastating threat to life and property along the U.S. Atlantic seaboard and Gulf of Mexico, and, thus a better understanding of their long-term frequency and causes is needed (Diaz and Pulwarty, 1997; Elsner and Kara, 1999). Recent studies suggest that hurricane frequency is related to multidecadal-scale variations in environmental parameters such as Atlantic sea surface temperatures and vertical wind shear and the climate modes forcing these parameters (Pielke and Landsea, 1998; Goldenberg et al., 2001). The relatively short record of systematic, instrumental, meteorological observations creates difficulty for discerning long-term (multidecadal) trends and fluctuations in tropical cyclone activity or to differentiate natural versus anthropogenic components of these trends. Prior to *ca*. 1900, systematic records of hurricane occurrence are fragmentary and rely predominately on documentary records

such as ship logs and news media. The development of geological proxies for tropical cyclone activity may provide a basis for evaluation of decade- to century-scale variations in tropical cyclone activity and their relationship to long-term climate variations (Liu, 2000). Tree rings provide a uniquely high-resolution and precisely dated record of climate that can be extended back for centuries, and even millennia. This study reports the first tree-ring isotope proxy record of tropical cyclone activity, moisture stress events, and multi-decadal variations in climate, based on a 227-year record of seasonal $\delta^{18}O$ values of α-cellulose in tree-rings from pines in the southeastern United States.

5.3 Capturing a Hurricane Record in Tree-Ring Isotopes

Organic oxygen isotopes in tree-ring α-cellulose mainly reflect the isotopic composition of the source water, dampened by physiological factors including carbonyl-water interactions during biosynthesis, xylem water–sucrose exchange, and leaf water evaporative enrichment (Saurer et al., 1997a; Anderson et al., 2002; Weiguo et al., 2004). Physiological effects tend to be very similar for a given species grown in the same environment (Anderson et al., 2002). Thus, large inter- and intra-annual differences in the oxygen isotope composition of cellulose from an individual tree, or like species from a given field area, most likely reflect changes in source water compositions.

For conifers having shallow root systems, such as slash (*Pinus elliottii* Engelm.) and longleaf (*Pinus palustris* Mill.) pine, the source water is most likely directly related to soil water, which itself is sourced by precipitation, and relative humidity (Anderson et al., 2002). Groundwater contributions would be minimal. Tropical cyclones produce large amounts of precipitation with distinctly lower (by as much as 10-20‰) $\delta^{18}O$ values than

typical low-latitude thunderstorms (Lawrence et al., 1998, 2002). Better organized and longer-duration tropical cyclones, such as major hurricanes (class 3+ Saffir-Simpson Scale), are likely to be associated with larger magnitude and geographically more extensive isotopic depletions. Evidence of isotopically depleted precipitation may persist in surface and soil waters for several weeks after a large event (Lawrence, 1998; Tang and Feng, 2001), and will be incorporated into cellulose during tree growth, capturing an isotopic record of tropical cyclone activity. The magnitude of storm-related isotopic depletions incorporated into cellulose will depend on many factors, including the size and proximity of the storm rain bands to the tree, the amount of storm precipitation available to the tree, and preexisting soil moisture conditions.

Evaporative enrichment of soil water will eventually ameliorate the low ^{18}O signal (Lawrence, 1998). The ephemeral nature (*i.e.,* several weeks) of hurricane-related ^{18}O-depleted soil water suggests it is captured only in the cellulose produced in the weeks following a storm event. Slash and longleaf pine tree rings preserve distinct earlywood (EW; growth in the early portion of the growing season) and latewood (LW; growth in the later portion of the growing season) components (Fig. 4) that can be separately analyzed to obtain seasonally-resolved isotope compositions. Hurricanes most typically impact the southeastern United States during typical LW growth months of August through October (Landsea 1993) although some tropical/subtropical storms can occur as early as May and impact EW values. Accordingly, we hypothesize that hurricane activity results in relatively ^{18}O-depleted LW cellulose. Evaporative enrichment of oxygen isotope ratios in soil and leaf water due to moisture stress conditions may also be recorded by tree-ring cellulose isotope compositions (Sternberg, et al., 1989; Saurer, et

al., 1997b). Seasonal moisture stress may thus result in EW (spring moisture stress) or LW (summer/fall moisture stress) ^{18}O-enrichments. On the basis of these observations, we hypothesize that an oxygen isotope proxy record of both tropical cyclone occurrence and seasonal moisture stress is preserved in tree-ring α-cellulose in slash pine and longleaf pine.

5.4 Materials and Methods

Several large slabs from felled slash pines (30.84°N; 83.25°W) and subfossil longleaf pine from nearby Lake Louise (30.43°N; 83.15°W), southern Georgia, were collected. The range of growing season temperature is modest (27–33ºC) and most precipitation is derived from nearby Gulf of Mexico or Atlantic sources (Bryson and Hare, 1974). Slash pine and longleaf pine are common in the coastal plain region of the southeastern United States, in well to moderately-well drained loamy sand soils, and have been shown to produce consistent annual rings (Grissino-Mayer et al., 2001). Slash pine is used for 1960-1997 records and subfossil longleaf pine is utilized for years 1770-1960. Fifteen years of overlap in measurements (1960-1975) show that EW and LW track similar relative changes in δ^{18}O, although compositions in longleaf pines are consistently 1 to 2‰ more positive compared to slash pine.

Slabs from these trees were chronologically dated using standard crossdating techniques (Stokes and Smiley, 1996). The EW and LW segments (Fig. 4) were separately cut into slivers (~40μm) to obtain seasonal resolution. Prior to α-cellulose extraction, pine resins were removed by accelerated solvent extraction using 3:1 toluene and reagent alcohol at 125˚C and 1500 psi. An internal standard, Sigma-Cellulose™, was

treated using the same approach, without change to its isotopic compositions within uncertainty limits. Alpha-cellulose was extracted from whole wood using soxhlet extraction methods (Green, 1963; Loader et al., 1997). Oxygen isotope compositions of α-cellulose (80 to 100μg) were analyzed using a TC/EA interfaced with a Finnigan MAT Delta Plus continuous flow mass spectrometer (Werner et al., 1996; Saurer et al., 1998) at the University of Tennessee Knoxville and are reported relative to V-SMOW. Both the internal standard and NBS-19 were routinely analyzed and α-cellulose samples were run in triplicate. A 2σ standard deviation for our samples of ±0.33 most likely reflects some natural variation at the sub-seasonal scale, as discussed in a later section. The proxy results are compared to instrumental meteorological observations of precipitation and temperature (for 1905-1997) from Valdosta, Georgia, and nearby stations (http://lwf.ncdc.noaa.gov), major tropical cyclone tracks (1851-1997; HURDAT; http://www.weather.unisys.com), Palmer Drought Severity Indices (1895-1995; PDSI cell ID 131; http://www.ncdc.noaa.gov/paleo/usclient2.html), and tree-ring reconstructed (PDSI; for 1770-1894).

5.5 Decadal to Multidecadal-Scale Variations in $\delta^{18}O$

A 227-year record of tree-ring cellulose $\delta^{18}O$ values is shown in Figure 5. The isotopic values for EW and LW appear to be overprinted on systematic, decadal to multi-decadal-scale variations. While grossly trending together, EW and LW values are similar over some time intervals (~within 1‰; *cf.* 1977-1992, 1930-1946, 1860-1865, and ~early 1820s), but different in others (2‰ or more; *cf.* 1845-1860, 1890-1924 and 1947-1976). These intervals most likely reflect systematic variations in seasonal temperature or

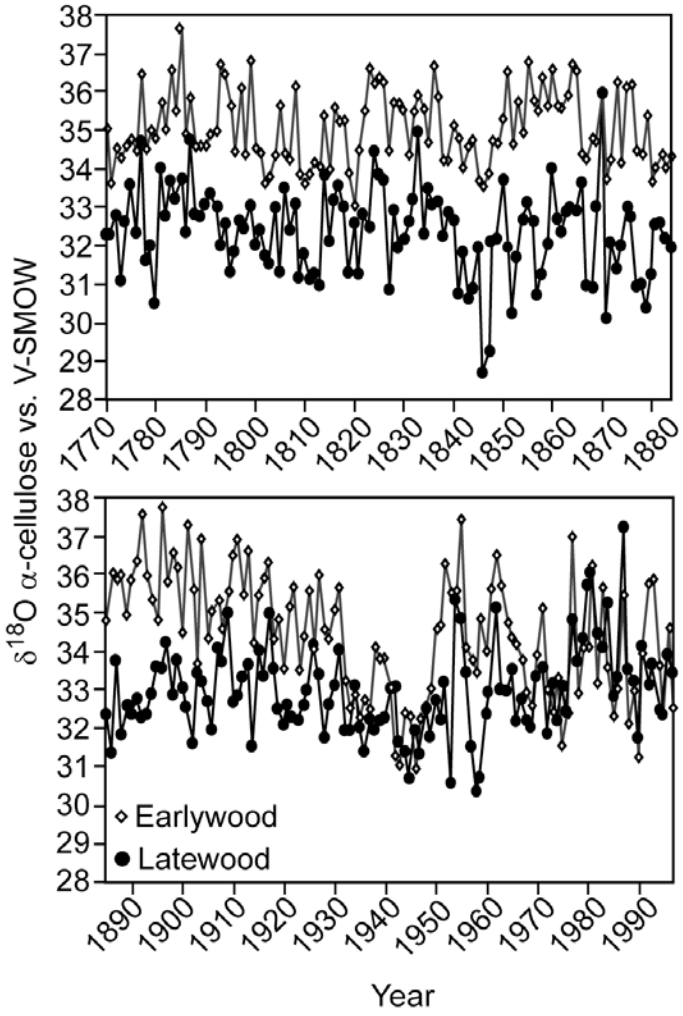

Figure 5. Earlywood (EW) and latewood (LW) trends of $\delta^{18}O$ spanning 227 years (1770–1997). The isotopic compositions indicate long-term, oscillatory trends corresponding to decadal to multi-decadal climate modes.

sources of normal precipitation controlled by larger scale climate modes, such as the Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, etc. (Enfield et al. 2001, Rogers and Coleman, 2003; D'Arrigo et al., 2001; Hurrell, 1995). To detect isotopic anomalies in the time series, we used a one-year ARMA (autoregressive moving average) modeling technique [AR (1); Fig. 6]. ARMA models are mathematical models of persistence or autocorrelation in a time series (http://www.ltrr.arizona.edu). Negative LW residuals (i.e. residuals < -1 where residuals = observed – model predicted values) indicate anomalously light oxygen isotope compositions and are shown in the shaded area of Figure 6. The darker shading for LW residual values in the range -0.5 to -1.0 are still about 2-3 times larger than our analytical certainty and are still considered anomalous. Positive anomalies, with LW (or EW) residuals >1, are identified with the dashed lines in Figure 6 and 7.

5.6 The Proxy Record of Tropical Cyclone Activity

The last half-century of instrumental records allow for the most accurate and complete knowledge of tropical cyclone intensity, precipitation and storm track. To determine the efficacy with which tree-ring $\delta^{18}O$ values capture a record of hurricane activity or seasonal moisture stress, the LW residual record from 1940-1997 is compared to instrumental meteorological observations (Fig. 6a) from Valdosta, Georgia, including daily precipitation (http://lwf.ncdc.noaa.gov) records and major tropical cyclone tracks passing within ~300 km of Valdosta (HURDAT; http://www.weather.unisys.com). EW residual record is also investigated for pre- and early season tropical/subtropical storms (Fig. 7). We note that for every year in which tree-ring isotope compositions are anomalously negative (<-1.0 residual) for the LW season, southern Georgia is affected by

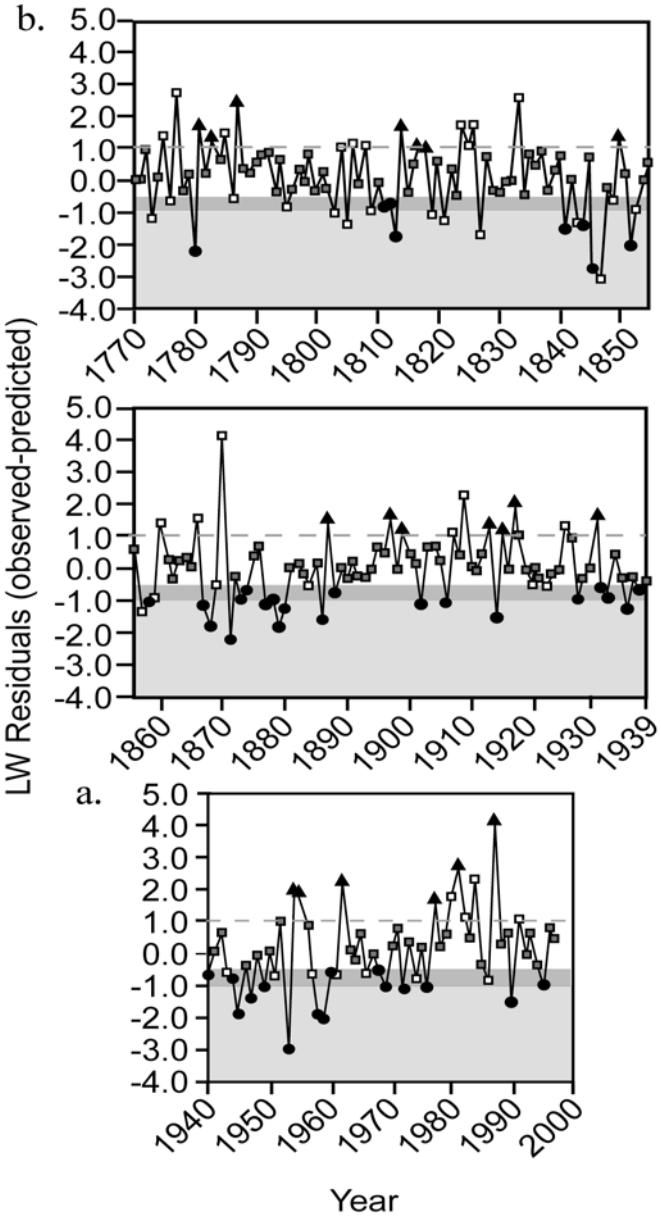

Figure 6. One -year autoregression modeling [AR(1)] of the LW (summer-fall) time series data. The great majority of tropical cyclones (TC) (filled circles) occur during late summer-fall and TC stand out as the negative LW residuals (residual=observed-predicted value). The 1940-1997 (a.) record is compared to instrumental records of TC occurrence (see text). Positive residuals reflect moisture stress events (filled triangles), defined by PDSI. Open squares represent no instrumentally recorded or documented event.

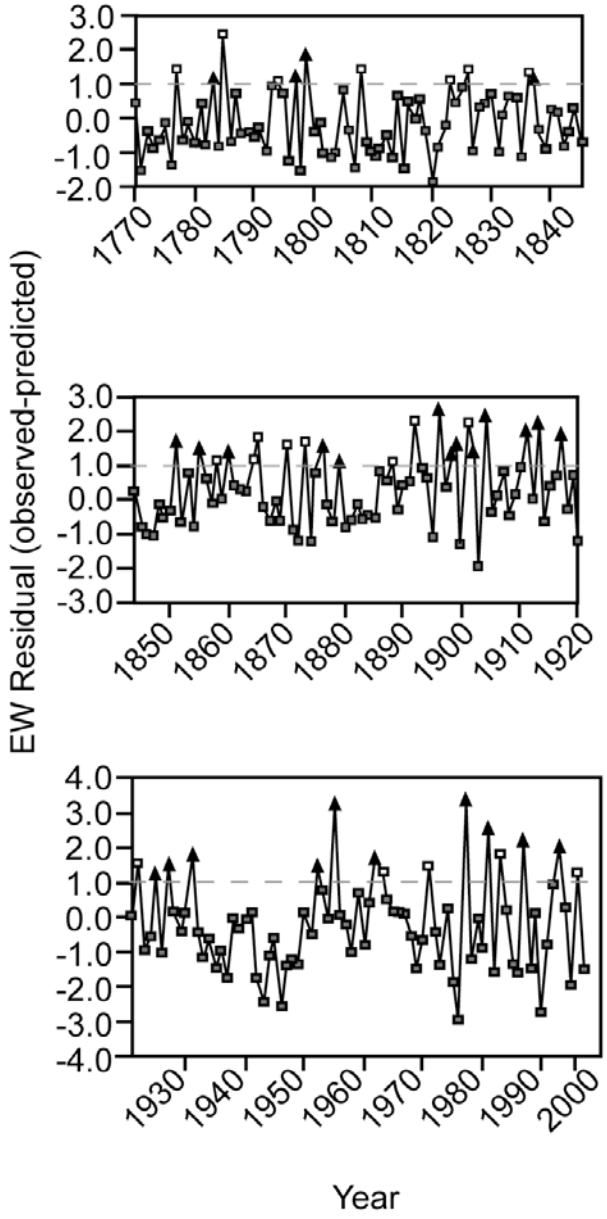

Figure 7. One-year autoregression modeling [AR(1)] of the EW (winter-spring) time series data. Positive EW residuals (<+1 residual) likely reflect winter-spring moisture stress effects (dashed line). Filled triangles represent recorded moisture stress from regional recorded and tree-ring width inferred PDSI values; open squares represent anomalous positive residuals that do not correspond to a recorded/inferred PDSI moisture stress event; and gray squares represent no anomalous event.

documented tropical cyclone activity and many years with residuals <-0.5 are also affected (Fig. 6). Hurricane events are recorded even when local rainfall amounts are modest. Hurricane Helene (1958) delivered only 2.5 cm of rainfall to the study area (http://lwf.ncdc.noaa.gov), yet the 1958 LW residual indicates a hurricane (Fig. 6a). EW oxygen isotopes are more complicated and only two known tropical/subtropical storms appear in the residual series [1976- Subtropical Storm #1 (May 22-25); 1995- Hurricane Allison (June 5-6)] (Fig. 7).

Tropical cyclones are dynamic weather phenomena that do not produce precipitation uniformly across the storm's spatial extent. Tropical cyclones show large variations in rainfall distributions during the storm's evolution that is mostly due to changes in windshear, sea surface temperatures, moisture distribution, storm intensity, storm location, and storm translation speed. Actual rainfall from a tropical cyclone may cover as little as 25% or possibly less of the total area within 500km of the storm center. Maximum rainfall for all tropical cyclones occurs in the front quadrants with varying degrees toward the right or left depending on the intensity of the storm (right – tropical storms; left – major hurricanes) (Lonfat et al., 2004). For example, Hurricane David (1979) passed within ~200 km of Valdosta (September 3) as a category 1 hurricane, but no significant rainfall was recorded while the storm was within 400 km of Valdosta (Valdosta 3E station; http://cdo.ncdc.noaa.gov/dly/DLY). As a consequence, no oxygen isotope record of Hurricane David is observed in the tree rings from Valdosta.

Sampling for this study included material from the entire LW portion of the ring. Because of the ephemeral nature of the hurricane-related isotope depletion in soil water, only a portion of the LW cellulose may pick up the ^{18}O-depletion, and the averaged

seasonal isotope ratios may mask less intense storm activity. For example, in 1953, the study area was affected by Hurricane Florence. The 1953 LW residual for sample was -1.5. In a second round of sampling, the 1953 LW was split into early-latewood (ELW) and late-latewood (LLW) components. Florence made landfall over the panhandle of Florida as a category 2 storm (http://www.ncdc.noaa.gov) during the ELW portion of the growing season (September). The entire isotopic anomaly was present in the ELW, with a more significant LW residual of -3.0. Thus, higher-resolution sampling of the tree-ring will improve the significance of the anomaly and clarify the interpretation of samples with modest (-0.5 to -1.0) LW residuals (Fig. 6a).

Interpretation of the proxy record (Fig. 6) shows close agreement that the 1950 decade was the busiest for hurricane activity in the 20th century (Goldenberg et al., 2001). The proxy record further supports historical records suggesting significant tropical cyclone activity for the southeastern United States between 1850–1910, in particular, six storms in the 1870 decade (http://www.ncdc.noaa.gov; Mock, 2004), even though only one hurricane (1871; the largest 1870 decade anomaly; Fig. 6) appears to have made a direct hit on the Georgia coast. Offshore hurricanes, such as an 1858 storm (Fernandez-Partagas and Diaz, 1995; 1996), may also be recorded. Previous studies suggest hurricane-related isotope depletions can be significant even several hundred km from the eye (Lawrence and Gedzelman, 1996).

Tropical cyclone reconstructions based on historical documents are spatially and temporally limited for the Atlantic and Gulf coasts and the tree-ring isotope proxy results presented here suggest several previously undocumented storms may have impacted remote areas. For example, although there is no historical record of a 1780 event in

southern Georgia, the results (Fig. 6) suggest that the "Great Hurricanes" of 1780 may have impacted the area (Fig. 6) (Sandrik and Landsea, 2003). Two events are indicated in 1847 and 1857 (Fig. 6). No event has yet been historically documented for 1847, however, the results for 1857 complement limited historical data suggesting an event (http://www.ncdc.noaa.gov; Mock, 2004). In addition to Hurricane #7 in 1879, which was a tropical storm at the time of impart near lower Georgia, documents also suggest a major storm event of unspecified origin (Sandrik and Landsea, 2003), which the tree-ring oxygen isotopes indicate may have been a hurricane (Fig. 6).

5.7 Seasonal Moisture Stress

Moisture stress events are established using instrumental determinations of regional and state Palmer Drought Severity Indices (http://www.ncdc.noaa.gov/paleo/usclient2.html; PDSI cell ID 131) for 1895-1995 and tree-ring reconstructed PDSI (1770-1894). Years for which moisture stress has been established near the study area are identified as triangles in Figures 6 and 7. Moisture stress events are clearly associated with positive residual values in the tree-ring isotope data. PDSI is a regional record and the "extra" moisture stress events indicated by the isotope proxy are interpreted to be the result of more locally-controlled, seasonal soil moisture deficit in the study area.

The superposition of isotopic extremes related to moisture stress and tropical cyclones can complicate interpretation of the isotope proxy hurricane record. For example, several notable hurricanes in the 1890 decade, such as the Sea Islands Hurricane of 1893 and hurricanes in 1896 and 1898 (Sandrik and Landsea, 2003), are not detected in the proxy record. This decade coincides with PDSI tree-ring reconstruction of

mild to severe moisture stress in the study he area (http://www.ncdc.noaa.gov/paleo/usclient2.html). As well, hurricanes are dynamic systems and factors affecting hurricane precipitation isotope ratios (e.g., the intensity, duration, and proximity of the storm to the study area) change throughout the life of the storm (Gedzelman et al., 2003). Tree-ring isotopes capture only a point in time and space of the event. Unless precipitation falls on the study area, a proxy record of the event will not be recorded. Without direct instrumental records of precipitation, this proxy best provides positive evidence, rather than negative evidence, of an event.

5.8 Conclusion

Important climate characteristics affecting the frequency of tropical cyclones may operate on time scales beyond modern instrumental records and compound the development of geological proxies of hurricane activity and climate. Few proxies offer the exactly datable, intra-annual resolution of tree rings. Oxygen isotopes in tree rings may provide a valuable proxy for tropical cyclone and moisture stress occurrence and help to develop the extended records necessary to evaluate natural versus anthropogenic impact on hurricane frequency. The isotope record of tree-ring cellulose presented here supports its use as a new proxy for hurricanes and moisture stress extending beyond historical records for the southeastern United States.

Chapter VI. Large Climate Oscillations Captured in Tree-Ring Oxygen Isotopes: Implications for Future Research

6.1 Abstract

A seasonally-resolved, oxygen isotope time series preserved in alpha-cellulose from longleaf and slash pines in the southeastern United States reveals annual to multidecadal oscillations in $\delta^{18}O$ values that can be correlated to climate modes influencing regional temperatures and precipitation sources and hurricane frequency. The Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, and El Niño Southern Oscillation can be correlated to variations in the isotopic composition of tree-ring cellulose. Instrumental indices of the Atlantic Multidecadal Oscillation show a strong negative correlation with earlywood oxygen isotope values from 1876 until ~1950s. A breakdown in the correlation after 1950 coincides with a major shift in the Pacific Decadal Oscillation-El Niño Southern Oscillation from warm to cool conditions (1947–1976 Cool Period II) that was followed by one of the strongest La Niña episodes (1954-1956) in the last 50 years. Latewood tree-ring oxygen isotopes from the decade of the 1950s strongly correlate to Niño 3.4 indices.

Spectral analysis of the latewood tree-ring oxygen isotope compositions reveal significant periodicities of ~82.7, 33.7, 7.9, and 5.1 years. Earlywood isotopes capture only a 36.4 year periodicity. Solar influences such as the Gleissberg Period (82.7) may reflect the effects of solar activity on climate parameters such as moisture source and temperature in the southeast. Periodicities in the range ~33–36 years are likely related to climate forcing caused by oscillations in solar activity, possibly related to the Bruckner Cycle. Shorter-term periodicities may be related to the effects of El Niño Southern

Oscillation (5.1) and Pacific Decadal Oscillation (7.9) on hurricane frequency. Indeed, ~5-6 and 7-9 year periodicities have been related to the frequency of tropical-only and baroclinically-enhanced Atlantic hurricanes. Correlation of the isotopic time series with large-scale climate oscillations may therefore clarify climate modes controlling precipitation and seasonal temperature variations, as well as their relationship to periods of high or low hurricane frequency.

6.2 Introduction

Climate in the southeastern U.S. is fundamentally influenced by large atmospheric and oceanic oscillations, including the Atlantic Multidecadal Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation, and the El Niño Southern Oscillation. Oxygen isotope compositions from tree rings in the southeastern U.S. respond predominantly to source water and temperature, and both parameters may be linked to the overriding climate factors responsible for variations in the precipitation source and/or seasonal temperature. The isotopic time series has also been shown to capture a record of extreme events (hurricanes and moisture stress). Spectral analysis of the time series data further reveals significant periodicities related to climate variation or tropical cyclone activity in the southeastern United States.

The Atlantic Multidecadal Oscillation (AMO) is the leading mode of low frequency sea surface temperature variability in the North Atlantic basin (0–70˚N), fluctuating over a 0.4˚C range (Kerr, 2000). Over the measured record of SST (1856–Present), a 65–80 year cycle is observed, with warm periods existing 1860–1880 and 1940–1960 and cool periods occurring 1905–1925 and 1970–1990 (Enfield *et al*. 2001). The AMO is linked to multi-year precipitation anomalies over North America (Enfield et

al. 2001; McCabe et al. 2004). Warm (cool) phases of the AMO result in increased (decreased) winter cyclonic activity and rainfall across the southeastern U.S. (Kalnay et al. 1996). The AMO is believed to affect Atlantic hurricane formation, directly and indirectly, by modulating the strength of El Niño events and African moisture stress frequency (Folland et al. 1986).

The North Atlantic Oscillation (NAO) is a quasi-decadal oscillation between the Icelandic low (Stykkisholmur, Iceland) and the Azores high (Lisbon, Portugal) pressure systems. Major hurricane activity in the Atlantic/Caribbean/Gulf of Mexico basins appears to increase during periods of negative NAO activity and decrease during positive NAO periods (Cayan, 1992; Elsner *et al*., 2000). The NAO also influences where major hurricanes tend to track. During positive NAO years, major hurricanes more commonly strike the east coast. During negative NAO years, major hurricanes are steered on a more southerly course, to strike the Caribbean/Gulf Coast region (Elsner et al. 2000; Molinari and Mestas-Nuñez, 2003).

Recent studies have shown a strong Pacific Decadal Oscillation (PDO) signal in precipitation patterns for areas along the eastern seaboard. The PDO is an index of decadal scale atmospheric-oceanic variability expressed as dominant modes of North Pacific sea surface temperatures (SST) (D'Arrigo *et al*. 2001). For the 20th century, PDO fluctuations occur with periodicities of 15-25 years and 50-70 years (Minobe 1997). Warm/positive PDO regimes have been identified for the periods 1925–1946 and 1977 to the mid 1990s. Since then, the PDO is believed to be switching to a cool/negative phase. Cool/negative PDO regimes occurred in 1890–1924 and 1947–1976 (Mantua *et al*., 1997;

Minobe 1997). Tree-ring studies have suggested that the strength and punctuation of the PDO has changed over time (D'Arrigo *et al*. 2001).

El Niño Southern Oscillation (ENSO) events in the equatorial Pacific may be strengthened by the PDO, and ENSO has been demonstrated to affect hurricane activity along the southeastern seaboard. ENSO events are stronger and more likely to occur when the ENSO phase is coincident with the respective PDO phase, i.e., El Niño and warm/positive PDO; La Niña and cool/negative PDO (Gershunov and Barnett, 1998). During the past 50 years, the five strongest El Niño events occurred in 1982/1983, 1997/1998, 1957/1958, 1986/1987, and 1972/1973 (Hare and Mantua, 2001) and the five strongest La Niñas years are 1973/1974, 1954–1956, 1964–1966, 1988–1990, and 1949–1951 (Wolter and Timlin 1993, 1998).

Climate conditions in the southeastern U.S. appear to be affected by the PDO, especially the winter and spring seasons. The PDO has been linked to summer rainfall and moisture stress variability in the U.S. (Nigam *et al*., 1999). The warm PDO phase relates to wet conditions for the southeastern U.S., and cool PDO phase relates to warm, dry conditions (Mantua 2000, 2002). Analysis of climate trends in North Carolina (1949–1998) reveals that precipitation patterns of the eastern U.S. seaboard correlate well with the phases of the PDO (Boyles and Raman, 2003).

6.3. Study Location

Longleaf (*Pinus paulstris*, Mill.) and slash (*Pinus elliottii*, Engelm.) pines from southern Georgia are utilized in this study. Slash pines were cut down on the Valdosta State University campus (30.84°N; 83.25°W) during the 1990s and sections of these trees have been archived for paleoclimate research. Subfossil longleaf wood from nearby Lake

Louise (30.43°N; 83.15°W) was also collected. Lake Louise contains longleaf tree stump specimens dating back to the 1400s (Grissino-Mayer- personal communication). Slash pine and longleaf pine are found in the coastal plain region of the southeastern United States and have been shown to produce consistent annual rings (Grissino-Mayer *et al.,* 2001). The modern average annual temperature at the study site is 20.3°C (69°F), and average annual precipitation is 112 cm (44 in).

6.4 Methodology

All wood samples were sanded, statistically correlated, and cross-dated using COFECHA to obtain the exact age (Stokes and Smiley, 1996). The earlywood (EW) and latewood (LW) segments were separately cut into wood slivers (~40μm) with a razor blade (Fig. 4). Resins were removed from the shavings using an Accelerated Solvent Extraction 300 (ASE 300) with a 3:1 toluene:reagent alcohol solvent mixture. Alpha cellulose was extracted from samples following methods first established by Green (1963) and modified by Loader *et al*. (1997) and this study (p.28-35). Oxygen isotopes are analyzed using a quantitative high temperature carbon reduction elemental analyzer (TC/EA) interfaced with an isotope ratio mass spectrometer (IRMS) at the University of Tennessee, Knoxville. Approximately 100μm (±30μm) of each sample is weighed and loaded into silver caps. The silver caps are placed into an auto sampler where the samples are sequentially pyrolized in a graphite reactor oven at 1450˚C and TC/EA oven set at 100˚C. The CO liberated is carried in a He-stream to the Finnigan MAT Delta Plus XL continuous flow isotope ratio mass for measurement of $^{18/16}$O ratios. Internal standards were compared with NBS-19 standard (n=19; standard deviation = 0.32).

6.5 Results and Discussion

Comparisons of the oxygen isotope time series and variations in the AMO were made using an AMO smoothed index that uses a 10-year running mean of Atlantic SST anomalies north of the equator (1876–1997) (Enfield *et al*. 2001). Yearly averaged AMO SSTs exhibit a correlation ($r=-0.40$) ($p<0.01$) to EW oxygen isotopes for the southeast (Fig. 8). The inverse relationship between EW oxygen isotope values and AMO appears to breakdown around 1950. Correlations between EW isotopes and AMO values from 1876-1950 are significantly higher, $r= -0.65$ ($p<0.01$), while post-1950 correlations are weaker and positive, $r=+0.32$ ($p<0.05$). LW oxygen isotopes show little significant correlation with the smoothed AMO index over any significant portion of 121-year time series. Between 1876-1950 LW isotopes exhibit a slight negative correlation with AMO anomalies $r=-0.35$ ($p<0.001$), but post-1950 shows no correlations with AMO anomalies. Comparisons with individual AMO warm (1860–1880 and 1940–1960) and cool (1905–1925 and 1970–1990) phases do not show significant correlations with tree-ring isotopes.

Niño 3.4 SST Index (1950-1997) was utilized for assessing the relationship between ENSO events and tree-ring oxygen isotopes of the southeast. ENSO events in the 1950s very strongly correlate to LW tree-ring oxygen isotopes (Table 5, Fig. 9) (http://www.cpc.nccp.noaa.gov/data/indices/). Months of April and June-December collectively show $r= -0.69$ ($p<0.05$) with an overall $\Delta SST=2ºC$ for the decade (Niño 3.4 SST Index). The 1950s were significantly impacted by La Niña events and consequent moisture stress. In the southeast, decreases in precipitation are observed in winter during La Niña events (Roswintiarti *et al*. 1998). One of the five strongest La Niña episodes occurred in 1954–1956 (Wolter and Timlin 1993, 1998). A severe PDSI instrumental

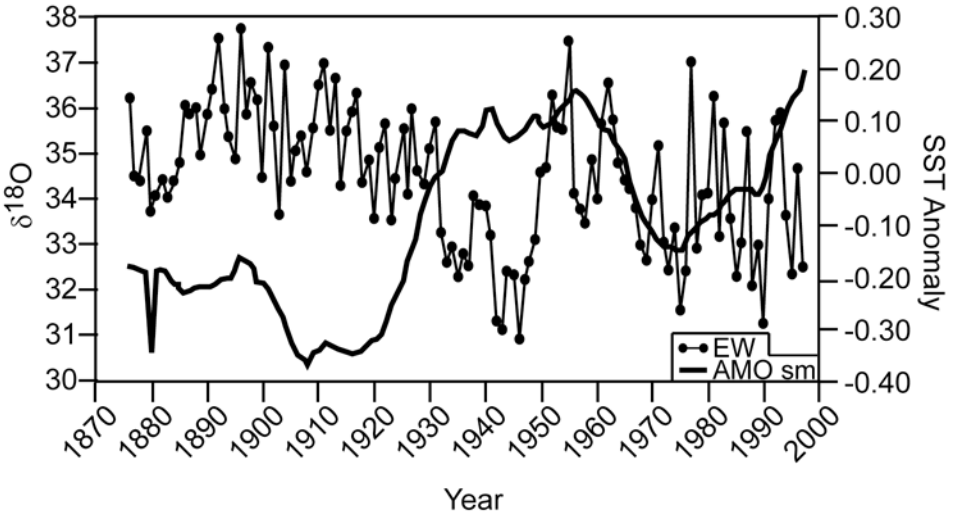

Figure 8. Tree-ring $\delta^{18}O$ (vs. V-SMOW) EW values compared with SST anomalies in the North Atlantic (AMO indices smoothed with a 10 year running average). A strong negative correlation is consistent until ~1950.

Table 5. Niño 3.4 monthly correlations with EW and LW isotopes by decade.

Decade	Season	Month	r-value	Significance Level
1950	LW	April	-0.688	0.028
		June	-0.795	0.006
		July	-0.699	0.024
		August	-0.644	0.045
		September	-0.646	0.044
		October	-0.690	0.027
		November	-0.690	0.027
		December	-0.690	0.027
1960	NSC			
1970	NSC			
1980	EW	May	+0.635	0.049
1990	NSC			
(NSC = No Significant Correlation)				

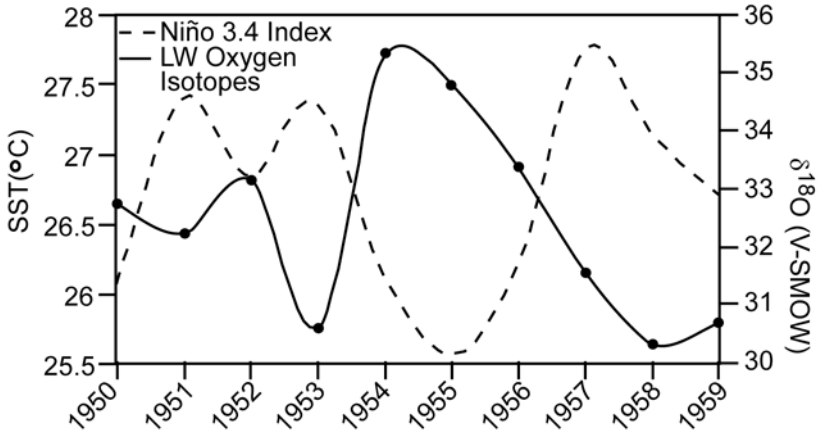

Figure 9. Niño 3.4 SST index compared with LW oxygen isotopes show a strong inverse relationship during the 1950s. Months that significantly correlated with LW isotopes are April and June through December.

moisture stress is recorded 1954 and 1955 for both EW and LW seasons. LW residuals suggest a moisture stress in both years but EW residuals only show moisture stress conditions for 1955 (Fig. 6 and 10).

The decade of the 1950s was more strongly influenced by La Niña than El Niño episodes (MEI ENSO Index; http://www.cdc.noaa.gov/ENSO/enso.mei_index.html; MEI ENSO Index is a weighted average of the main ENSO features). The 1950s were very active with 4 tropical cyclones recorded by the tree rings (1953, 1957-1959). La Niña conditions are more conducive to tropical cyclone activity in the Atlantic and Caribbean basin but create moisture stress conditions for the southeast U.S. Confounding isotope signals may occur when tropical cyclones and moisture stress events overlap in the same LW season. For example, in 1950 Hurricanes Easy (01-09 September) and King (13-19 October) tracked within ~87km of the study area (HURDAT). Precipitation was recorded during the days of closest approach for both storms, but no oxygen isotope depletion is observed in the tree rings (http://lwf.ncdc.noaa.gov/servlets/DLY). Monthly PDSI values indicate a mild to moderate LW moisture stress for 1950 and thereby muted the oxygen isotope signal from the tropical cyclone precipitation.

The 1980s exhibit a significant positive correlation of Niño 3.4 SST index with EW isotopes for May ($r=+0.64$, $p<0.05$). In the southeast, increases in precipitation are observed in winter during El Niño events (Roswintiarti *et al*. 1998). During the past 48 years (1949–1997), two of the five strongest El Niño events have occurred in the 1980s, 1982/1983 and 1986/1987 (Hare and Mantua, 2001). The strong El Niño events of the 1980s may have influenced precipitation source waters for the southeast and was recorded in the EW isotopes.

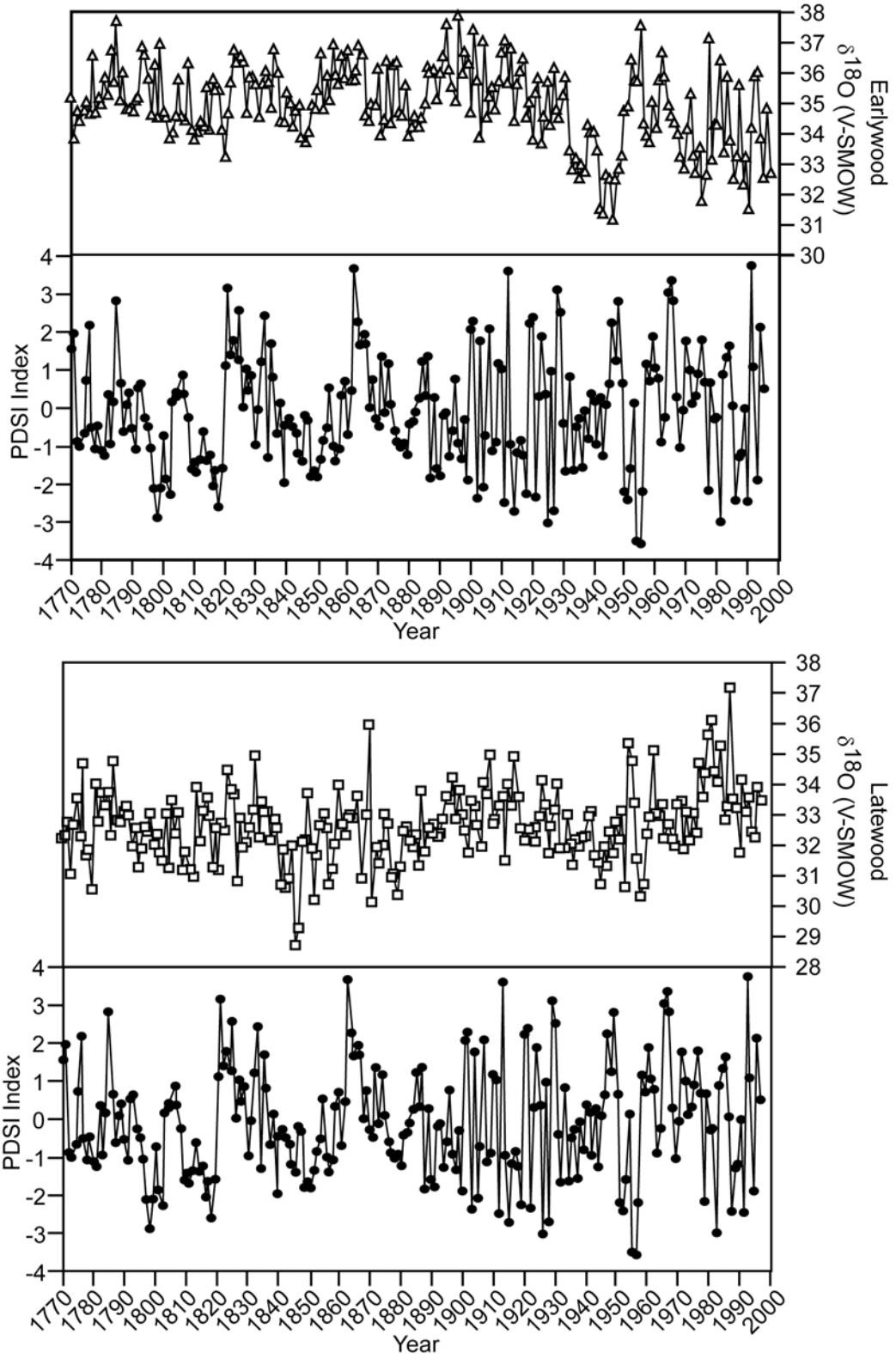

Figure 10. PDSI indices and EW and LW tree-ring oxygen isotopes.

The most recent cool and warm phase of the PDO exhibits a robust influence on the southeast. Teleconnections from the Pacific appear to affect predominately LW oxygen isotope values. Cool Period II (1947–1976) significantly correlates with LW oxygen isotope values for months April to December (Table 5). A cool PDO phase will bring warm, dry conditions for the southeast (Mantua 2000) that is expected to result in overall enrichment of oxygen isotope compositions. This negative relationship (i.e., cool/negative PDO and positive values of $\delta^{18}O$) is particularly noticeable in light of the opposing isotopic effects of the busy tropical cyclone season superimposed on the isotopic record of this period, most notably the 1950s. More tropical cyclones impacted the study area during the Cool Period II than any other PDO phase (Fig. 11). Indeed, the main hurricane months of August through October express some of the lowest correlations. The PDO is largely responsible for the strength and frequency of ENSO events (Mantua 2000). Constructive interference between PDO and ENSO SST phases amplify the effects of these oscillations. One of the largest PDO-ENSO swings occurred ~1947 with a warm to cool transition (Bondi *et al*. 2001). The Cool Period II (1947–1976) coincides with the strong La Niña events of the 1950s. Warm Period II (1977–1997) correlates positively with LW November indices **(**Table 6) (ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest). This warm period coincides with two of the strongest El Niño events during the 1980s. Warm PDO phase is thought to bring cool/wet conditions to the southeast (Mantua 2000), but the positive correlation suggests drier conditions. Part of the reason may be due to ENSO since summers during El Niño events experience drier than normal conditions (Roswintiarti et al. 1998). Despite two of the wettest years on record for the area (1988

Table 6. PDO and correlations with EW and LW oxygen isotope values.

	Earlywood			Latewood		
	Month	r-value	Significance Level	Month	r-value	Significance Level
Cool Period I 1900-1924	Nothing	—	—	Nothing	—	—
Warm Period I 1925-1946	Nothing	—	—	Nothing	—	—
Cool Period II 1947-1976	July	-0.396	0.05	April	-0.508	0.01
				May	-0.499	0.01
				June	-0.508	0.01
				July	-0.513	0.01
				August	-0.407	0.05
				September	-0.418	0.05
				October	-0.415	0.05
				November	-0.394	0.05
				December	-0.511	0.01
Warm Period II 1977-1997	Nothing	—	—	November	+0.516	0.05

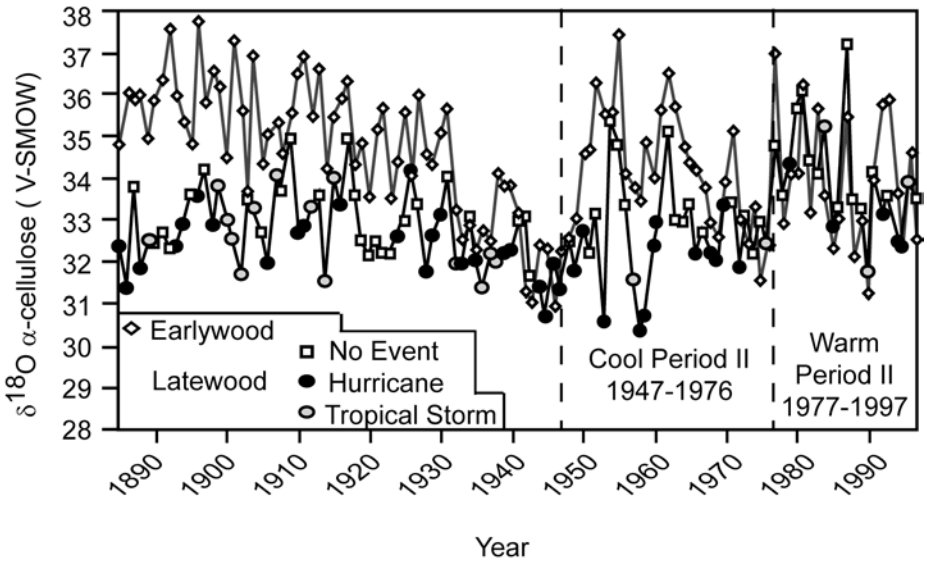

Figure 11. EW and LW oxygen isotope time series with PDO Cool Period II and Warm Period II. Both time series trend together during each PDO phase but Cool Period II exhibits a greater absolute difference between corresponding EW and LW values. The earlier portion of the time series (~1885-1950) appears to be dominated by AMO effects while the later period (~1950-1997) appears to be dominated by PDO effects.

and 1994) coinciding with Warm Period II, more dry years occur over this interval than wet years. Despite Warm Period II exhibiting below average growing season low temperature for the latewood over an 87-year period, oxygen isotopes do not show any notable relative depletion during this time interval as might be expected from lower temperatures suggesting that precipitation source is more influential than temperature (Fig. 11 and 12). Both EW and LW oxygen isotope time series positively correlate during Cool Period II (r=+0.46) and Warm Period II (r=+0.58), but Cool Period II exhibits a distinctly greater difference in absolute values of corresponding EW and LW values (Fig. 11).

The NAO does not significantly correlate with long-term oxygen isotope variations in the tree-ring record. Although the NAO exhibits a strong influence on tropical cyclone landfall, our restricted sample area is not spatially or temporally expansive enough to significantly detect these differentiations. Most tropical cyclones impacting the study area from the Gulf of Mexico region do occur in the negative phase of the NAO, but this is a very small and indefinitive subset of samples. This study site in southern Georgia captures a tropical cyclone record derived from both the Gulf/Caribbean and the Atlantic basin, so the lack of any significant storm tracking correlations is not surprising.

Spectral analysis reveals significant periodicities affecting latewood and earlywood oxygen isotope compositions of cellulose from these southeastern pines. Spectral analysis was performed using free downloadable software AnalySeries 1.2 (Paillard et al. 1996) (http://www.ngdc.noaa.gov/paleo/softlib/softlib.html). In latewood, significant periodicities of 82.7, 33.7, 7.9, and 5.1 years were determined (Fig.13);

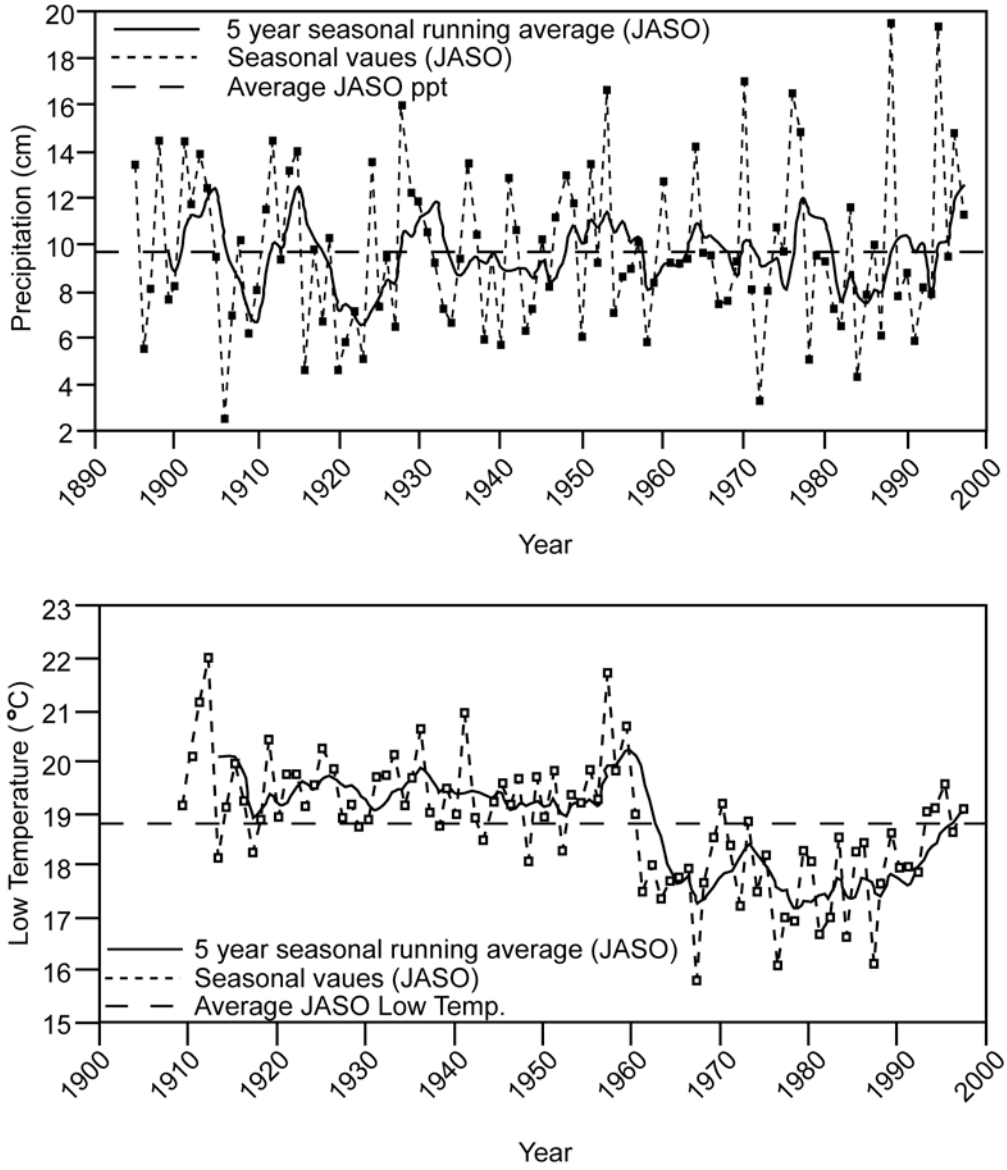

Figure 12. Local yearly averaged precipitation and low temperature values for the latewood growing season.

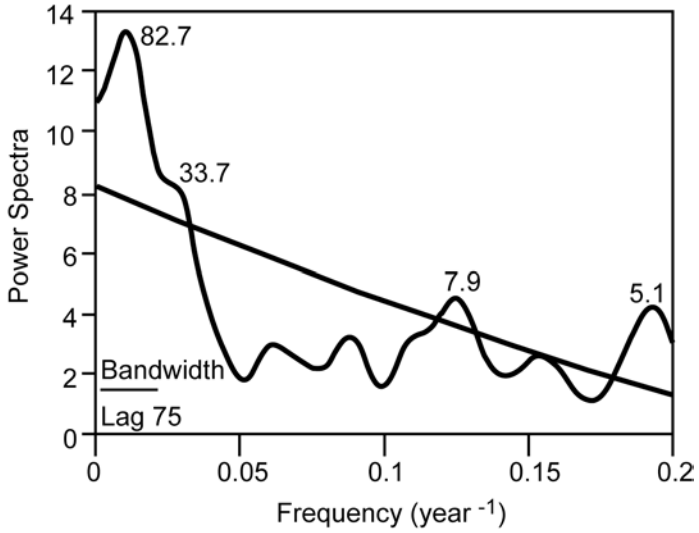

Figure 13. Spectral analysis of LW oxygen isotopes from 1770–1997. Significant periodicities occur at ~ 82.7, 33.7, 7.9, and 5.1 years.

earlywood shows only a 34.6-year periodicity (Fig. 14). The Gleissberg Period oscillates on ~80 year cycle and is a well-known solar cycle related to the 11-year Schwabe Cycle (sun spot cycle) (Sonnett and Finney, 1990). Both LW and EW oxygen isotopes suggest a periodicity at ~33–36 years (Fig. 13 and 14). A ~36-year solar cycle exhibits a strong influence on PDO and ENSO fluctuations and intensity (Diaz and Pulwarty, 1994; Landscheidt, 2000) that may be affecting the impact of these climate oscillations on source water and temperature in the southeast. Periodicities at 5.1 and 7.9 years in the LW oxygen isotopes are likely related to North Atlantic hurricane frequency. Elsner et al. (1999) have discovered semidecadal oscillations of 5–6 years and near-decadal oscillations of 7–9 years in North Atlantic hurricane activity. The semidecadal oscillation is associated with ENSO events and relates to the frequency of tropical-only type of tropical cyclones. The near-decadal oscillation correlates to the frequency of baroclinically enhanced hurricanes that may be influenced by changes in Atlantic SSTs, and are possibly related to variations in solar activity.

6.6 Conclusion

The oxygen isotope fingerprint of the precipitation source is seasonally captured in earlywood and latewood cellulose. The breakdown of tree-ring oxygen isotope correlations with AMO indices during the 1950s corresponds to the timing of strong ENSO and PDO effects. The Cool Period II and following Warm Period II of the PDO combined with the reinforcement of the respective ENSO phases may have sufficiently shifted precipitation sources to effectively disrupt the AMO signal during the last ~50 years. Warm phases of the PDO result in decreased hurricane activity for the southeastern seaboard while cool PDO phases show increased hurricane activity based on tree-ring

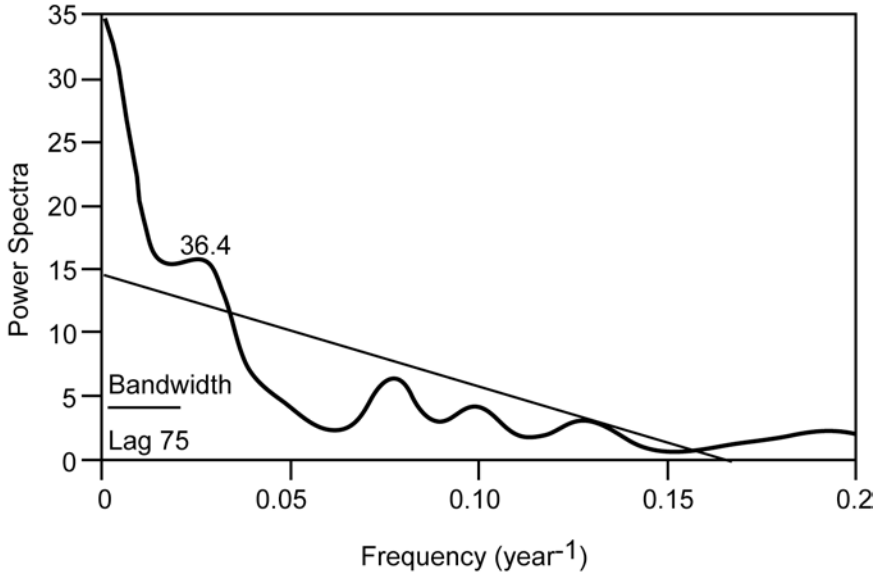

Figure 14. Spectral analysis of EW oxygen isotopes from 1770–1997. Significant periodicities occur at ~ 36.4 years.

oxygen isotope reconstruction from the southeastern U.S. Spectral analysis suggests significant solar influences affect the oxygen isotopes of the tree rings. This occurrence is likely due to the influence of solar activity on the climate regimes currently at work affecting the southeast. Significant periodicities related to large climate oscillations (i.e 36-year PDO and ENSO periodicity) and to tropical cyclone frequency and type (tropical-only 5-6 years and baroclinically-enhanced 7-9 years) support the robust nature and versatility of this climate proxy.

Chapter VII. Southeastern Climate in a Portion of the Little Ice Age (1580-1650): Evidence from Tree-ring Oxygen Isotopes

7.1 Abstract

Oxygen isotopes from tree-ring cellulose of longleaf pines in southern Georgia capture a snapshot of climate conditions during a portion of the Little Ice Age (1580–1650) for the southeastern U.S. The oxygen isotopes primarily reflect changes in precipitation source and moisture stress. Isotopic ratios of cellulose during this time period are very similar to modern values (1895–1997). The results of this study support previous studies that suggest the southeastern U.S. did not experience dramatic climate effects of the Little Ice Age. A lack of negative isotope anomalies over 1580-1640 suggests that tropical cyclone activity was low, but activity increased noticeably in the 1640s.

7.2 Introduction

High-resolution proxies are essential tools to evaluate climate reconstruction, especially over the last few centuries. Assessment of the effect and extent of global warming will be more accurate only with a solid understanding of past climate. Discerning natural climate variation from anthropogenically-induced changes will aid in predicting the evolution of future climate. The Little Ice Age (LIA), a late Holocene cool episode (~1550–1850), is often considered a global event (i.e., Crowley and North, 1991), but recent work suggests that the effects of the LIA are more localized (i.e., Folland *et al*. 1990; Bradley and Jones 1992). The LIA includes roughly synchronous advances of North American and European glaciers (Grove 1988; Bradley and Jones 1992). The question arises to what geographic extent in North America were these cold

episodes evident. In context of the whole Northern Hemisphere, the LIA is considered only a modest cooling of <1˚C temperature change compared to late 20th century, with particular areas subjected to more or less pronounced cooling (Bradley and Jones 1993; Jones *et al*. 1998; Mann *et al*. 1998). Oxygen isotope records from western Atlantic coral reveal a SST cooling of ~1˚C during the LIA (Druffel 1982). For areas of the southeastern U.S., spring rainfall reconstructions using tree rings from bald cypress indicate that the LIA was not strongly reflected in prolonged rainfall deficits or surpluses over the Carolinas and Georgia (Stahle and Cleaveland, 1994). Tropical cyclone activity during the LIA is thought to be relatively high compared to the modern record (Lamb, 1995; Moore 1998), but, historical documents covering this time period are sparse both temporally and spatially. Therefore, a climate proxy tracking tropical cyclone and moisture stress activity may provide insight into the climate environment of this time period for the southeastern U.S. This study investigates a time slice within the LIA. Oxygen isotopes from tree rings are used to assess climate change during 1580–1650 compared with the modern record from southern Georgia (1895–1997). Possible tropical cyclone and moisture stress events are evaluated.

7.3 Oxygen Isotopes and Tree Rings

The oxygen isotopes of α-cellulose are predominately related to precipitation, temperature, and relative humidity (Saurer, *et al*., 1997a; Lipp *et al*., 1996; Epstein et al., 1977). Although temperature is important considering the isotopic fractionation of the source water, little or no temperature dependence exists affecting the net biological fractionation in tree rings (Roden and Ehleringer, 2000). Oxygen isotopes in tree-rings are affected by four major factors: (1) source water $\delta^{18}O$ composition (soil water), (2)

leaf-water enrichment from evaporative effects, (3) biological fractionation (27‰), and (4) exchange occurring between unenriched xylem water and sucrose oxygen atoms during the transfer of sucrose produced in the leaves to sites of cellulose production (Anderson et al. 2002 and references therein). For this study, isotopic variables are (1) changes in source water and (2) moisture stress effects due to stomatal stress from either high temperatures or lack of moisture source. Variable factors (3) and (4) basically remain constant for the species. Evaporative enrichment of oxygen isotopes in soil and leaf water due to moisture stress conditions may be recorded in the tree-ring cellulose (Sternberg, et al., 1989; Saurer, et al., 1997b). The general soil type for the study area is well-drained loamy sand within the Coastal Plain of Georgia (Stevens 1979). The shallow root systems of the conifers used in this study also minimize possible fractionation of ^{18}O in soil water and greatly reduce the chance of groundwater infiltration into the roots. Isotopic fractionation does not occur during the uptake of soil water via the roots or during the transfer of water to the leaves via the xylem (Forstel and Hutzen, 1983).

7.4 Oxygen Isotope Mechanics in Tropical Cyclone Systems

Tropical cyclones are dynamic mesoscale convective systems whose extreme precipitation efficiency may permit the weather phenomenon to be traced isotopically in proxies through geologic time. Tropical cyclones produce precipitation with distinctly lower $\delta^{18}O$ values (< -6‰) than other tropical rain systems (~ -6 to 0‰) (Dansgaard 1964; Nicolini et al. 1989; Lawrence and White 1991). Two basic physical factors govern $\delta^{18}O$ values in precipitation and meteoric water vapor: (1) Isotopic fractionation during condensation, where ^{18}O is preferentially incorporated into the more condensed phase; (2) Diffusive isotopic exchange between falling rain and ambient vapor, which

result in a ^{18}O enrichment of the falling rain and a decrease in vapor compositions. Over time, this process lowers the isotope ratio of ambient vapor near the surface and results in a temporal decrease in isotope ratios of precipitation during storm events (Miyake et al., 1968; Lawrence and Gedzelman 1996; Gedzelman et al., 2003). Large, organized, and long-lived storms, such as tropical cyclones, particularly amplify these isotope effects. The oxygen isotope ratio of water vapor and condensate sharply decreases with cloud height (Dansgaard, 1953; Ehhalt and Östlund 1970). In relatively long-lived storm systems such as tropical cyclones, the total mass of rain produced far outweighs the mass of vapor in the storm at any given moment, and the high condensation efficiency and great cloud height may result in $\delta^{18}O$ values of precipitation that approach the $\delta^{18}O$ of the source water vapor (Lawrence and Gedzelman, 1996). Within the tropical cyclone, oxygen isotope depletion increases radially towards the eye. Lofting of rain or sea surface spray during strong updrafts may enrich water vapor in the eyewall, replenishing ^{18}O isotopes deep within the cyclone (Gedzelman et al. 2003). Gedzelman et al. (2003) hypothesize that tropical system rains can develop low isotope ratios within 24 to 48 hours after organized secondary circulation occurs, long preceding hurricane strength status. The extent of ^{18}O depletion in tropical cyclone precipitation is not a measure of the strength of the storm, but rather a possible indicator of circulation intensity. According to the model of Gedzelman et al. (2003), initial intensification of a tropical cyclone involves preferential incorporation of ^{16}O in snow that is thrust into the upper troposphere. This snow is temporally isolated from the water vapor pool available for precipitation, creating a pulse of isotopically enriched precipitation. Over time, this snow is flushed downward resulting in an abrupt depletion in precipitation. Efficient recycling of water, with

diffusive isotopic exchange between inflowing vapor and falling rain in rain bands, leads to inward decrease of ratios towards the eye. Low ratios of oxygen isotopes have still been observed near the outer fringe (Lawrence et al., 2002).

7.5 Methodology and Study Site

Several large slabs from felled slash pines (30.84°N; 83.25°W) and subfossil longleaf pine from nearby Lake Louise (30.43°N; 83.15°W), southern Georgia, were collected. The range of growing season temperature is modest (27−33ºC) and most precipitation is derived from nearby Gulf of Mexico or Atlantic sources (Bryson and Hare, 1974). Slash pine and longleaf pine are common in the coastal plain region of the southeastern United States, in well to moderately-well drained loamy sand soils, and have been shown to produce consistent annual rings (Grissino-Mayer et al., 2001). Slash pine (*Pinus elliotii*, Engelm.) is used for 1960-1997 records and longleaf pine (*Pinus paulstris*, Mill) is utilized for years 1960-1895 and subfossil longleaf for1580-1650. Fifteen years of overlap in measurements (1960-1975) show that EW and LW track similar relative changes in $\delta^{18}O$, although compositions in longleaf pines are consistently 1 to 2‰ more positive compared to slash pine.

Slabs from these trees were chronologically dated using standard crossdating techniques (Stokes and Smiley, 1996). The EW and LW segments (Fig. 4) were separately cut into slivers (~40μm) to obtain seasonal resolution. Prior to α-cellulose extraction, pine resins were removed by accelerated solvent extraction using 3:1 toluene and reagent alcohol at 125˚C and 1500 psi. An internal standard, Sigma-Cellulose™, was treated using the same approach, without change to its isotopic compositions within uncertainty limits. Alpha-cellulose was extracted from whole wood using soxhlet

extraction methods (Green, 1963; Loader et al., 1997). Oxygen isotope compositions of α-cellulose (80 to 100μg) were analyzed using a TC/EA interfaced with a Finnigan MAT Delta Plus continuous flow mass spectrometer (Werner et al., 1996; Saurer et al., 1998) at the University of Tennessee Knoxville and are reported relative to V-SMOW. Both the internal standard and NBS-19 were routinely analyzed and α-cellulose samples were run in triplicate. A 2σ standard deviation for our samples of ±0.33 most likely reflects some natural variation at the sub-seasonal scale.

7.6 Results

The seasonal EW and LW oxygen isotope time-series for the period 1580–1650 were modeled with an AR-1 regression model to amplify anomalous values, which occur as residual values > 1.0 or < -1.0. A modern part of the tree ring record for this area (1895–1997), covering the extent of instrumental meteorological records (http://lwf.ncdc.noaa.gov), is used for comparison of the extent and frequency of tropical storm and moisture stress events. The most intense season of tropical storm activity, August to October, occurs during the LW growing season of these pines. LW residuals and oxygen isotopes were compared with modern tropical cyclone records (HURDAT) and compiled historical records (Sandrik and Landsea, 2003). Seasonal moisture stress records from EW and LW residuals during the LIA are compared with tree-ring based reconstructed PDSI values for that time period and the modern record is compared with instrumental PDSI values (http://www.ncdc.noaa.gov/paleo/usclient2.html) to assess how well the oxygen isotopes of these tree rings capture a moisture stress signal.

Modern instrumental records of tropical cyclone and moisture stress activity match well with corresponding negative oxygen isotope residuals in tree rings for the last

102 years from southern Georgia. Positive EW and LW residual peaks are predominately associated with moisture stress events (Fig. 15 a and b). These same issues also affect LW values identifying tropical cyclone activity, but the large degree of isotope depletion of precipitation created by these storms allows an arbitrary distinction to be made. All years with LW values of less than –1 residual are associated with tropical storm disturbances and most LW values of less than –0.5 residual are also associated (Fig. 15b). Although oxygen isotopes from tree-ring α-cellulose are well connected with tropical cyclone and moisture stress occurrence, not all tropical cyclones historically documented or meteorologically observed are captured in the oxygen isotopes of the tree rings. The intensity of the storm and proximity and duration of the storm's rain bands are critical elements for adequate depleted precipitation (Lonfat et al. 2004).

Overall oxygen isotope values of both EW and LW from 1580–1650 appear to be less variable than the modern record. The isotope range for the modern data set for the last 70 years (1927–1997) in EW=6.6‰ (37.5‰ to 30.9‰) and in LW=6.9‰ (37.2‰ to 30.3‰). The oxygen isotope extremes for 1580–1650 exhibit a smaller range: EW=5.4‰ (37.3‰ to 31.9‰) and LW=5.3‰ (36.3‰ to 31‰). The overall oxygen isotope values for this time are similar to the modern data series but are slightly heavier (Fig. 16) (Appendix 2). This suggests that moisture source and/or temperature fluctuations were similar to or less marked during this period of the LIA compared with modern records. Other studies support a similar interpretation. Thorough spring rainfall analysis using bald cypress tree rings from Georgia and North and South Carolina reveal no outstanding prolonged spring rainfall deficits or surpluses during the LIA (Stahle and Cleaveland 1994). The EW isotope record measured here confirms this record. Summer precipitation

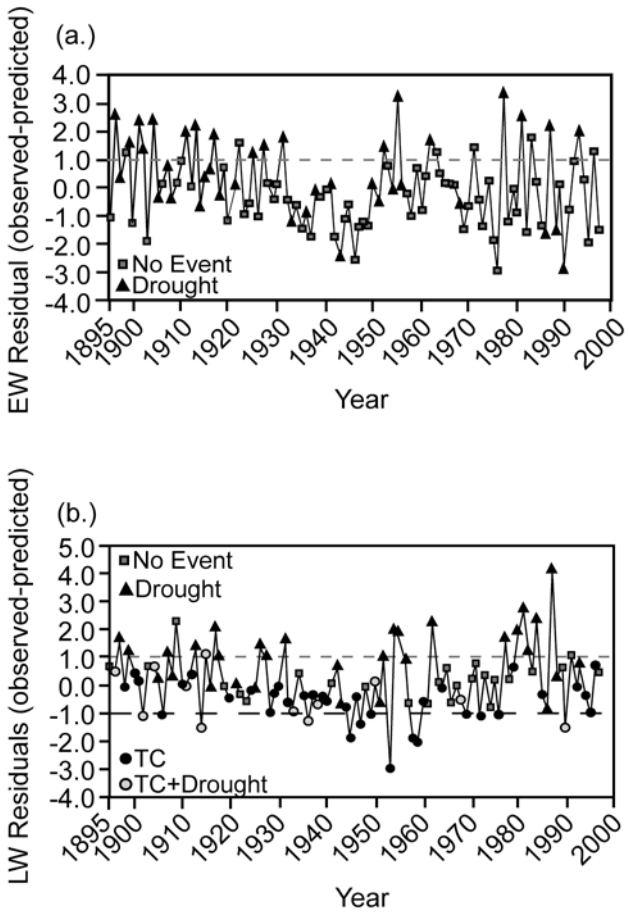

Figure 15. EW and LW residuals of oxygen isotopes covering the extent of instrumental records for the study area (1895–1997). The modern record is used as a reference for interpreting oxygen isotopes from the same area during the Little Ice Age. Residuals greater than 1 are usually associated with moisture stress and residuals less than -1 are usually associated with tropical cyclones.

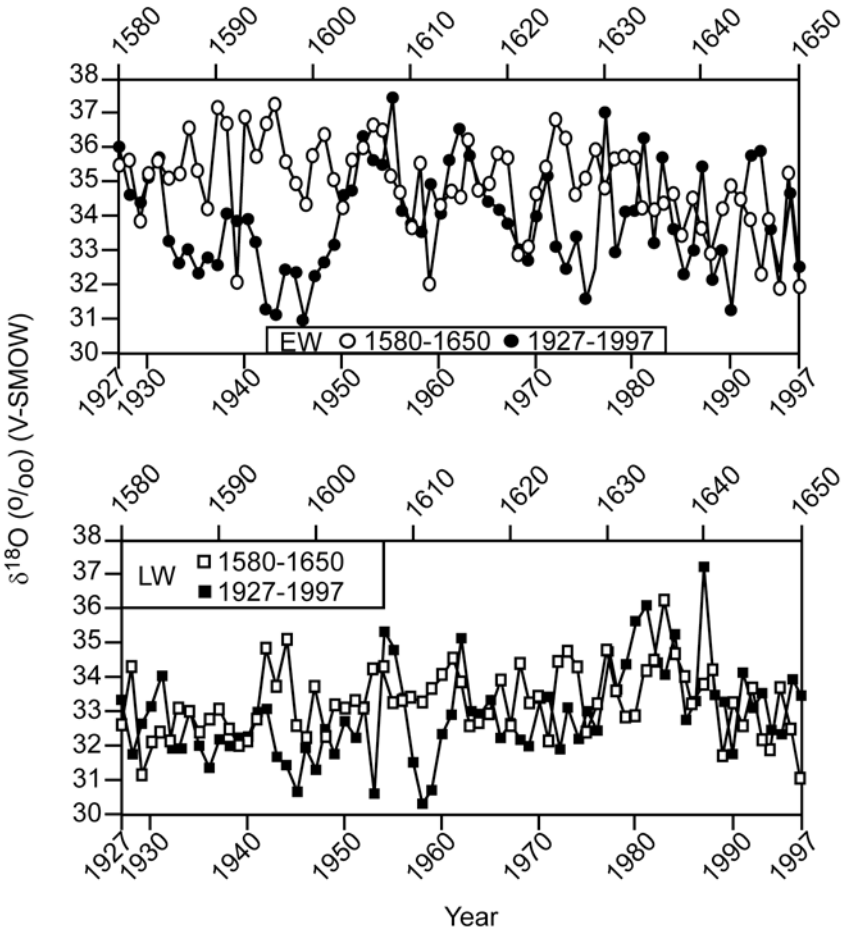

Figure 16. Modern tree-ring oxygen isotopes compared to a portion of the Little Ice Age. Both time series exhibit very similar values.

reconstruction using tree-ring width analysis of longleaf pines from southern Georgia suggests enhanced summer rainfall during the late 1500s and mid-1600s (Grissino-Mayer and Tepper, 2002), and, therefore, no prolonged moisture stress. This is consistent with the EW and LW residuals where the range is generally ±2 (Fig. 17) compared with the modern record with a general range of ±3 (Fig. 15). SST variability inferred from coral $\delta^{18}O$ and Sr/Ca ratios from Bermuda (1520–1603) suggests temperature variability similar to that of today (Kuhnert *et al*. 2002). Based on oxygen isotopes, the 70 years evaluated during the LIA (1580-1650) for southern Georgia do not appear to be anomalously cold or dry/wet.

Although previous studies suggest that the LIA was a time of great North Atlantic hurricanes exceeding the severity of modern times (Lamb, 1995; Moore, 1998), our data do not support frequent tropical cyclone activity for the southeast during most of the period 1580-1650 (Fig. 17). No known tropical cyclones impacted Georgia during the 70 year time interval but five tropical cyclone events, both onshore and offshore, are thought to have impacted northeast Florida (1589, 1591, 1599, 1638, and 1641) (Sandrik and Landsea 2003) and could have delivered tropical cyclone rainfall to southern Georgia. Four of these five years are associated with tree-ring indicated PDSI mild moisture stress (1589, 1599, 1638, and 1641) (Cook *et al*. 1999). The positive oxygen isotope anomaly associated with moisture stress may dampen negative oxygen isotope anomalies associated with tropical cyclone precipitation. Our oxygen isotope record appears to capture only one of the six historically-documented cyclones (1599). Based on the modern record of LW values ≤ -1 residual indicating tropical cyclone occurrence, the years 1580–1640 show moderately little activity with only four possible tropical cyclone

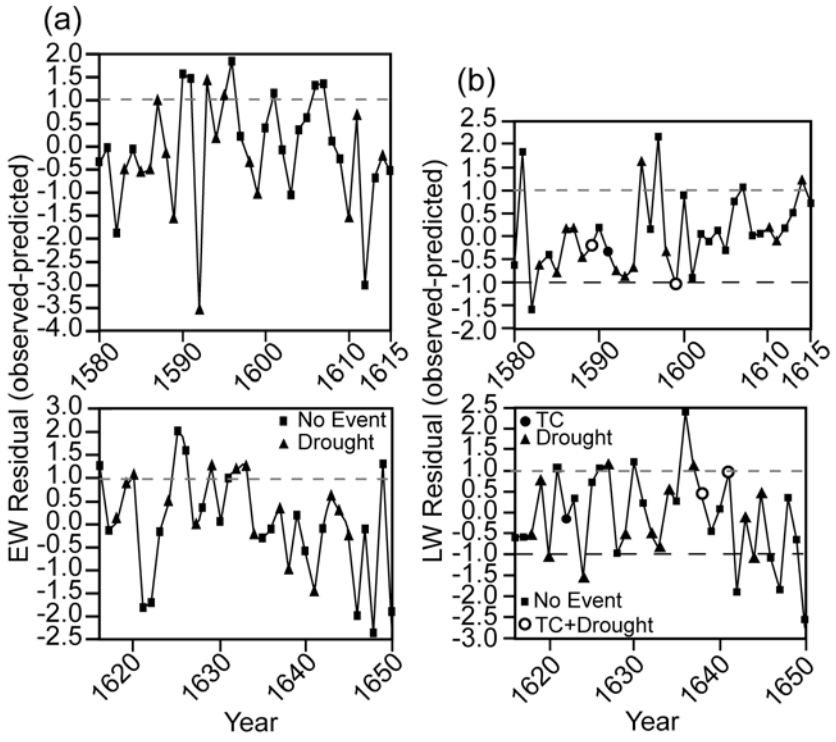

Figure 17. AR-1 residual values for EW and LW during the Little Ice Age. Tropical cyclones are generally associated with <-1 residual (LW) and moisture stress associated with <1 residual (EW and LW). Tropical cyclone activity appears to be minimal until the end of the time series.

years (1582, 1599, 1620, and 1624). Conversely, LW residuals from the last decade of the time series (1641-1650) suggest 5 years of potential tropical cyclone activity (1642,1644, 1646, 1647, and 1650) (Fig. 17). Indeed, equatorial east Africa during 1560–1625 experienced a severe moisture stress episode (Verschuren *et al*., 2000), which would have greatly reduced tropical cyclone formation originating from African waves. This reduction of tropical waves originating off the African coast may have greatly reduced the number of tropical cyclones that could have impacted the southeast during this time. Tropical cyclone activity appears to increase dramatically in the 1640s decade although none of these possible storms are yet historically documented. The end of the equatorial east African moisture stress in concert with a complex dynamic of climate oscillatory patterns possibly encouraged this apparent increase in tropical cyclone activity.

Instrumental PDSI indicated moisture stress for the modern series appear to be most effective during EW growth and that would predominantly reflect spring rainfall (Fig. 15). EW residuals from the Little Ice Age interval (1580-1650) suggest the EW season experienced moisture stress events during 18 of these years (Fig. 17). Although bald cypress tree-ring width reconstructions suggest spring rainfall was highly variable but overall above average between 1595–1614 for the southeast (Stahle and Cleaveland, 1994), the oxygen isotope residuals from the tree-ring record during this interval suggest 5 possible moisture stress events (1595, 1596, 1601, 1606, and 1607). Diminished southeast summer rainfall during early 1600s is reported from longleaf tree-ring analysis (Grissino-Mayer and Tepper, 2002). The LW isotopes from this study agree with this tree-ring interpretation showing a slight overall increase in oxygen isotopes during the

early 1600s when compared with modern values (Fig.16). LW residuals suggest 11 possible moisture stress events (residual > 1) from 1580–1650. The period 1590–1610 is considered one of the few periods during the LIA to exhibit hemispherically, if not globally, synchronous cool conditions (Jones and Bradley 1992). The oxygen isotopes of this study do not show a significant cooling trend (i.e., lower overall isotopic compositions). Changes in atmospheric circulation and moisture source may have been more influential on the oxygen isotopes observed from the tree rings in southern Georgia rather than temperature changes.

7.7 Conclusion

Oxygen isotopes from tree-ring cellulose covering the 1580–1650 time period do not exhibit extremes in values and are comparable to modern values. Tropical cyclone activity was less active compared to the modern time series from 1580–1640. During the last decade (1640–1650) tropical cyclone activity increased substantially. LIA Tropical cyclone activity is likely influenced by moisture stress conditions in the east African equatorial region and the complex interplay of large climate oscillations. Moisture stress events appear to be moderate during the time period and tropical cyclone activity appears moderate until the last decade of the 70 years observed. Historically documented tropical cyclone occurrence does not coincide very well with possible tropical cyclone reconstructions from tree-ring oxygen isotopes. This inconsistency is likely due to the sparse records of weather phenomena for this time period and area.

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Appendices

Appendix 1. Raw and Corrected Oxygen Isotope Values 1770-1997

(EW=earlywood; LW= latewood; MLW=middle latewood; LLW=late latewood}

Sample ID	Sample (6-10-03)	Raw ^{18}O Values	Corrected ^{18}O Values	EW/LW Average	Standard Deviation
VSU	Sigma Cell	7.69			
012	Sigma Cell	7.26			
	Sigma Cell	7.63			
	1970 EW	15.11	34.94	1970 EW	
	1970 EW	13.34	33.17	33.96	0.90
	1970 EW	13.94	33.77		
	1970 LW	14.35	34.18	1970 LW	
	1970 LW	12.41	32.24	33.33	0.99
	1970 LW	13.75	33.58		
	1971 EW	14.53	34.36	1971 EW	
	1971 EW	14.40	34.23	35.13	1.45
	1971 EW	16.97	36.80		
	1971 LW	12.97	32.80	1971 LW	
	1971 LW	13.94	33.77	33.41	0.53
	1971 LW	13.82	33.65		
	1972 EW	13.71	33.54	1972 EW	
	1972 EW	Lost	Lost	33.04	0.71
	1972 EW	12.71	32.54		
	1972 LW	12.25	32.08	1972 LW	
	1972 LW	11.85	31.68	31.88	0.20
	1972 LW	12.06	31.89		
	Sigma Cell	7.49	27.32		
	1973 EW	12.22	32.05	1973 EW	
	1973 EW	12.38	32.21	32.45	0.56
	1973 EW	13.26	33.09		
	1973 LW	12.87	32.70	1973 LW	
	1973 LW	13.52	33.35	33.09	0.35
	1973 LW	13.40	33.23		
	1974 EW	13.32	33.15	1974 EW	
	1974 EW	13.27	33.10	33.33	0.36
	1974 EW	13.91	33.74		
	1974 LW	12.35	32.18	1974 LW	
	1974 LW	13.38	33.21	32.17	0.56
	1974 LW	12.48	32.31		
	1975 EW	11.86	31.69	1975 EW	
	1975 EW	12.04	31.87	31.56	0.18
	1975 EW	12.22	32.05		
	1975 LW	13.10	32.93	1975 LW	

	1975 LW	13.55	33.38	33.00	0.35
	1975 LW	12.85	32.68		
	Sigma Cell	7.48	27.31		
VSU	Sample (6-10-03)				
012	Sigma Cell	8.47			
	Sigma Cell	8.22			
	Sigma Cell	8.02			
	1976 EW	12.79	32.64	1976 EW	
	1976 EW	12.22	31.66	32.41	0.67
	1976 EW	13.49	32.93		
	1976 LW	12.62	32.06	1976 LW	
	1976 LW	13.88	33.32	32.41	0.80
	1976 LW	12.41	31.85		
	1977 EW	18.16	37.60	1977 EW	
	1977 EW	16.36	35.80	37.00	1.04
	1977 EW	18.15	37.59		
	1977LW	14.01	33.45	1977 LW	
	1977LW	16.32	35.76	34.73	1.17
	1977LW	15.53	34.97		
	1978 EW	13.34	32.78	1978 EW	
	1978 EW	13.43	32.87	32.93	0.18
	1978 EW	13.69	33.13		
	1978 LW	14.55	33.99	1978 LW	
	1978 LW	14.16	33.60	33.60	0.22
	1978 LW	14.53	33.97		
	1979 EW	15.03	34.47	1979 EW	
	1979 EW	Lost	Lost	34.08	0.56
	1979 EW	14.24	33.68		
	Sigma Cell	7.55	26.99		
	1979 LW	15.77	35.21	1979 LW	
	1979 LW	15.10	34.54	34.37	0.94
	1979 LW	13.91	33.35		
	Sigma Cell	7.45	26.89		
017	1950 EW	15.00	34.44	1950 EW	
	1950 EW	15.35	34.79	34.58	0.19
	1950 EW	15.06	34.50		
	1950 LW	13.07	32.51	1950 LW	
	1950 LW	13.46	32.90	32.73	0.20
	1950 LW	13.34	32.78		
	1949 EW	12.34	31.78	1949 EW	
	1949 EW	15.29	34.73	33.10	1.50

	1949 EW	13.35	32.79		
	1949 LW	12.39	31.83	1949 LW	
	1949 LW	12.03	31.47	31.75	0.25
	1949 LW	12.52	31.96		
	Sigma Cell	7.57	27.01		
	1948 EW	13.44	32.88	1948 EW	
	1948 EW	Lost	Lost	32.62	0.37
	1948 EW	12.91	32.35		

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VSU	Sample (6-12-03)				
017	Sigma Cell	8.31			
	Sigma Cell	7.68			
	Sigma Cell	8.47			
	Sigma Cell	8.14			
	1960 EW	15.25	34.46	1960 EW	
	1960 EW	14.12	33.33	34.02	0.60
	1960 EW	15.05	34.26		
	1960 LW	12.93	32.14	1960 LW	
	1960 LW	13.28	32.49	32.33	0.18
	1960 LW	13.14	32.35		
	1961 EW	16.51	35.72	1961 EW	
	1961 EW	16.58	35.79	35.63	0.21
	1961 EW	16.18	35.39		
	1961 LW	13.87	33.08	1961 LW	
	1961 LW	13.61	32.82	32.91	0.14
	1961 LW	13.63	32.84		
	1962 EW	17.31	36.52	1962 EW	
	1962 EW	16.87	36.08	36.53	0.45
	1962 EW	17.77	36.98		
	Sigma Cell	8.13	27.34		
	1962 LW	16.48	35.69	1962 LW	
	1962 LW	15.30	34.51	35.10	0.59
	1962 LW	15.89	35.10		
	1963 EW	16.10	35.31	1963 EW	
	1963 EW	16.69	35.90	35.71	0.34
	1963 EW	16.70	35.91		
	1963 LW	14.08	33.29	1963 LW	
	1963 LW	13.71	32.92	33.00	0.26
	1963 LW	13.58	32.79		
	1964 EW	15.51	34.72	1964 EW	
	1964 EW	15.56	34.77	34.77	0.19
	1964 EW	15.21	34.42		
	1964 LW	13.69	32.90	1964 LW	

	1964 LW	Lost	Lost	32.94	0.06
	1964 LW	13.77	32.98		
	Sigma Cell	8.35	27.56		
REPEATS 1960'S OF 017					
VSU	Sample (6-13-03)				
	Sigma Cell	9.55			
	Sigma Cell	9.25			
	Sigma Cell	9.17			
017	1965 EW	16.20	34.65	1965 EW	
	1965 EW	15.41	33.86	34.38	0.45
	1965 EW	16.17	34.62		
	1965 LW	15.01	33.46	1965 LW	
	1965 LW	BAD TRACE	Lost	33.33	0.19
	1965 LW	14.74	33.19		
	1966 EW	15.99	34.44	1966 EW	
	1966 EW	15.64	34.09	34.20	0.21
	1966 EW	15.63	34.08		
	1966 LW	13.67	32.12	1966 LW	
	1966 LW	13.44	31.89	32.20	0.35
	1966 LW	14.13	32.58		
	Sigma Cell	8.45	26.90		
	1967 EW	15.51	33.96	1967 EW	
	1967 EW	15.30	33.75	33.79	0.15
	1967 EW	15.22	33.67		
	1967 LW	14.08	32.53	1967 LW	
	1967 LW	15.17	33.62	32.67	0.89
	1967 LW	13.41	31.86		
	1968 EW	14.71	33.16	1968 EW	
	1968 EW	14.45	32.90	32.98	0.16
	1968 EW	14.42	32.87		
	1968 LW	13.68	32.13	1968 LW	
	1968 LW	13.59	32.04	32.14	0.11
	1968 LW	13.81	32.26		
	Sigma Cell	8.67	27.12		
	1969 EW	14.54	32.99	1969 EW	
	1969 EW	14.01	32.46	32.61	0.34
	1969 EW	13.92	32.37		
	1969 LW	13.61	32.06	1969 LW	
	1969 LW	13.23	31.68	32.00	0.30
	1969 LW	13.82	32.27		
	Sigma Cell	8.97	27.42		
	1942 LW	14.48	32.93	1942 LW	
	1942 LW	14.63	33.08	33.09	0.17

	1942 LW	14.81	33.26		
	Sigma Cell	8.99	27.44		
	1941 EW	15.23	33.68	1941 EW	
	1941 EW	14.66	33.11	33.20	0.44
	1941 EW	14.36	32.81		
	1941 LW	14.73	33.18	1941 LW	
	1941 LW	14.74	33.19	32.97	0.37
	1941 LW	14.10	32.55		
VSU	Sample (6-10-03II)				
017	Sigma Cell	Lost			
	Sigma Cell	Lost			
	Sigma Cell	7.66	26.11		
	1948 LW	14.24	32.69	1948 LW	
	1948 LW	13.70	32.15	32.46	0.28
	1948 LW	14.09	32.54		
	Sigma Cell	7.91	26.36		
	1947 EW	13.61	32.06	1947 EW	
	1947 EW	13.82	32.27	32.24	0.17
	1947 EW	13.95	32.40		
	1947 LW	13.31	31.76	1947 LW	
	1947 LW	12.23	30.68	31.30	0.56
	1947 LW	13.00	31.45		
	Sigma Cell	7.89	26.34		
	1946 EW	12.04	30.49	1946 EW	
	1946 EW	12.91	31.36	30.92	0.44
	1946 EW	12.46	30.91		
	1946 LW	13.64	32.09	1946 LW	
	1946 LW	13.62	32.07	31.96	0.21
	1946 LW	13.26	31.71		
	Sigma Cell	7.94	26.39		
	1945 EW	13.86	32.31	1945 EW	
	1945 EW	13.66	32.11	32.31	0.20
	1945 EW	14.05	32.50		
	1945 LW	12.19	30.64	1945 LW	
	1945 LW	12.06	30.51	30.68	0.19
	1945 LW	12.44	30.89		
	Sigma Cell	7.52	25.97		
	1944 EW	13.10	31.55	1944 EW	
	1944 EW	14.26	32.71	32.40	0.75
	1944 EW	14.49	32.94		
	1944 LW	12.45	30.90	1944 LW	
	1944 LW	13.08	31.53	31.42	0.48
	1944 LW	13.39	31.84		

	Sigma Cell	7.68	26.13		
	1943 EW	12.96	31.41	1943 EW	
	1943 EW	12.67	31.12	31.12	0.30
	1943 EW	12.37	30.82		
	1943 LW	13.48	31.93	1943 LW	
	1943 LW	12.73	31.18	31.67	0.43
	1943 LW	13.46	31.91		
	Sigma Cell	7.55	26.00		
	1942 EW	12.68	31.13	1942 EW	
	1942 EW	13.25	31.70	31.29	0.36
	1942 EW	12.59	31.04		
VSU	Sample (6-13b-03)				
017	Sigma Cell	8.26	26.71		
	Sigma Cell	8.10	26.55		
	Sigma Cell	8.11	26.56		
	1940 EW	15.55	34.00	1940 EW	
	1940 EW	15.06	33.51	33.86	0.30
	1940 EW	15.61	34.06		
	1940 LW	13.83	32.28	1940 LW	
	1940 LW	13.87	32.32	32.27	0.06
	1940 LW	13.75	32.20		
	Sigma Cell	8.45	26.90		
	1939 EW	15.48	33.93	1939 EW	
	1939 EW	15.35	33.80	33.86	0.07
	1939 EW	15.40	33.85		
	1939 LW	13.76	32.21	1939 LW	
	1939 LW	13.85	32.30	32.23	0.06
	1939 LW	13.74	32.19		
	Sigma Cell	8.21	26.66		
	1938 EW	15.70	34.15	1938 EW	
	1938 EW	15.73	34.18	34.07	0.17
	1938 EW	15.43	33.88		
	1938 LW	13.38	31.83	1938 LW	
	1938 LW	13.30	31.75	31.96	0.30
	1938 LW	13.86	32.31		
	Sigma Cell	8.31	26.76		
	1937 EW	13.78	32.23	1937 EW	
	1937 EW	14.37	32.82	32.53	0.42
	1937 EW	Lost	Lost		
	1937 LW	14.26	32.71	1937 LW	
	1937 LW	13.29	31.74	32.18	0.49
	1937 LW	13.64	32.09		
	Sigma Cell	8.29	26.74		

	1936 EW	14.46	32.91	1936 EW	
	1936 EW	13.93	32.38	32.76	0.33
	1936 EW	14.54	32.99		
	1936 LW	12.59	31.04	1936 LW	
	1936 LW	13.13	31.58	31.35	0.28
	1936 LW	12.97	31.42		
	Sigma Cell	8.10	26.55		
	1935 EW	13.52	31.97	1935 EW	
	1935 EW	13.65	32.10	32.29	0.45
	1935 EW	14.35	32.80		
	1935 LW	13.42	31.87	1935 LW	
	1935 LW	13.43	31.88	32.02	0.26
	1935 LW	13.87	32.32		
	Sigma Cell	8.51	26.96		
VSU	Sample (6-14b-03)				
017	Sigma Cell	9.36			
	Sigma Cell	9.74			
	Sigma Cell	9.29			
	1930 EW	17.05	35.01	1930 EW	
	1930 EW	17.05	35.01	35.10	0.15
	1930 EW	17.31	35.27		
	1930 LW	15.03	32.99	1930LW	
	1930 LW	15.22	33.18	33.14	0.13
	1930 LW	15.29	33.25		
	1929 EW	16.23	34.19	1929 EW	
	1929 EW	16.26	34.22	34.34	0.23
	1929 EW	16.65	34.61		
	1929 LW	14.62	32.58	1929 LW	
	1929 LW	14.82	32.78	32.62	0.15
	1929 LW	14.53	32.49		
	Sigma Cell	9.30	27.26		
	1928 EW	16.52	34.48	1928 EW	
	1928 EW	16.68	34.64	34.60	0.10
	1928 EW	16.71	34.67		
	1928 LW	13.63	31.59	1928 LW	
	1928 LW	13.39	31.35	31.75	0.51
	1928 LW	14.36	32.32		
	Sigma Cell	9.31	27.27		
	1927 EW	17.82	35.78	1927 EW	
	1927 EW	18.16	36.12	35.99	0.18
	1927 EW	18.11	36.07		
	1927 LW	14.47	32.43	1927 LW	
	1927 LW	15.97	33.93	33.34	0.80

	1927 LW	15.71	33.67		
	Sigma Cell	9.13	27.09		
	1926 EW	15.84	33.80	1926 EW	
	1926 EW	16.57	34.53	34.09	0.39
	1926 EW	15.98	33.94		
	1926 LW	15.92	33.88	1926 LW	
	1926 LW	16.42	34.38	34.14	0.25
	1926 LW	16.20	34.16		
	Sigma Cell	9.32	27.28		
	1925 EW	16.76	34.72	1925 EW	
	1925 EW	18.11	36.07	35.54	0.72
	1925 EW	17.86	35.82		
	1925 LW	15.13	33.09	1925 LW	
	1925 LW	14.85	32.81	32.95	0.20
	1925 LW	Lost	Lost		
	Sigma Cell	9.48	27.44		
VSU	Sample (6-14-03)				
017	Sigma Cell	8.70			
	Sigma Cell	8.23			
	Sigma Cell	8.25			
	1934 EW	14.02	33.10	1934 EW	
	1934 EW	13.87	32.95	32.94	0.16
	1934 EW	13.70	32.78		
	1934 LW	13.66	32.74	1934 LW	
	1934 LW	13.87	32.95	33.01	0.31
	1934 LW	14.27	33.35		
	Sigma Cell	8.13	27.21		
	1933 EW	13.93	33.01	1933 EW	
	1933 EW	13.14	32.22	32.59	0.40
	1933 EW	13.46	32.54		
	1933 LW	12.71	31.79	1933 LW	
	1933 LW	13.21	32.29	31.91	0.34
	1933 LW	12.56	31.64		
	Sigma Cell	8.32	27.40		
	1932 EW	14.61	33.69	1932 EW	
	1932 EW	13.90	32.98	33.26	0.38
	1932 EW	14.03	33.11		
	1932 LW	12.69	31.77	1932 LW	
	1932 LW	12.96	32.04	31.90	0.14
	1932 LW	12.80	31.88		
	Sigma Cell	8.41	27.49		
	1931 EW	16.15	35.23	1931 EW	
	1931 EW	17.07	36.15	35.69	0.46

	1931 EW	16.61	35.69		
	1931 LW	15.33	34.41	1931 LW	
	1931 LW	14.83	33.91	34.02	0.35
	1931 LW	14.66	33.74		
VSU	Sample (6-19-03)				
012	Sigma Cell	9.65			
	Sigma Cell	9.68			
	Sigma Cell	9.85			
	1980 LW	18.09	35.69	1980 LW	
(17.18)	1980 LW	18.55	35.73	35.66	0.08
	1980 LW	18.39	35.57		
	Sigma Cell	9.76	26.94		
	1980EW	17.30	34.48	1980EW	
(17.15)	1980EW	16.90	34.08	34.13	
	1980EW	16.65	33.83		
	Sigma Cell	9.78	26.96		
	1981 LW	18.67	35.85	1981 LW	0.29
	1981 LW	18.78	35.96	36.07	
(17.28)	1981 LW	19.22	36.40		
	1981 EW	18.86	36.04	1981 EW	0.47
	1981 EW	18.72	35.90	36.24	
	1981 EW	19.59	36.77		
	Sigma Cell	9.52	26.70		
	1982 LW	17.99	35.17	1982 LW	0.64
	1982 LW	16.90	34.08	34.43	
(17.34)	1982 LW	16.87	34.05		
	1982 EW	17.42	34.60	1982 EW	1.26
	1982 EW	15.03	32.21	33.18	
	1982 EW	15.54	32.72		
	Sigma Cell	9.64	26.82		
	1983 EW	18.51	35.69	1983 EW	0.27
	1983 EW	18.22	35.40	35.68	
(17.38)	1983 EW	18.76	35.94		
	1983 LW	17.02	34.20	1983 LW	0.41
	1983 LW	17.25	34.43	34.09	
	1983 LW	16.46	33.64		
	Sigma Cell	9.45	26.63		
	1984 EW	16.18	33.36	1984 EW	0.24
	1984 EW	16.34	33.52	33.57	
	1984 EW	16.66	33.84		
(17.49)	1984 LW	17.93	35.11	1984 LW	0.66
	1984 LW	18.75	35.93	35.22	

	1984 LW	17.44	34.62		
	Sigma Cell	9.42	26.60		
	1985 LW	15.64	32.82	1985 LW	0.29
	1985 LW	15.60	32.78	32.78	
(17.42)	1985 LW	16.12	33.30		
	1985 EW	14.49	31.67	1985 EW	0.62
	1985 EW	15.14	32.32	32.30	
	1985 EW	15.73	32.91		
	Sigma Cell	9.59	26.77		
VSU	Sample (6-19b-03)				
012	Sigma Cell	9.78			
	Sigma Cell	9.57			
	Sigma Cell	10.00			
	1986 EW	15.63	33.40	1986 EW	0.33
	1986 EW	15.01	32.78	33.03	
	1986 EW	15.13	32.90		
	1986 LW	15.75	33.52	1986 LW	0.22
	1986 LW	15.32	33.09	33.30	
	1986 LW	15.52	33.29		
	Sigma Cell	9.37	27.14		
	1987 EW	17.93	35.70	1987 EW	1.10
	1987 EW	18.67	36.44	35.47	
	1987 EW	16.50	34.27		
	1987 LW	19.96	37.73	1987 LW	0.83
	1987 LW	18.46	36.23	37.18	
	1987 LW	19.82	37.59		
	Sigma Cell	9.80	27.57		
017	1924 EW	16.13	33.90	1924 EW	0.51
	1924 EW	17.15	34.92	34.42	
	1924 EW	16.67	34.44		
	1924 LW	14.82	32.59	1924 LW	0.24
	1924 LW	15.05	32.82	32.58	
	1924 LW	14.57	32.34		
	Sigma Cell	9.78	27.55		
	1923 EW	15.22	32.99	1923 EW	0.74
	1923 EW	16.59	34.36	33.51	
	1923 EW	15.42	33.19		
	1923 LW	14.18	31.95	1923 LW	0.49
	1923 LW	14.93	32.70	32.14	
	1923 LW	14.00	31.77		
	1922EW	17.94	35.71	1922EW	0.48
	1922EW	18.36	36.13	35.67	

	1922EW	17.41	35.18		
	1922 LW	14.50	32.27	1922 LW	0.22
	1922 LW	14.65	32.42	32.23	
	1922 LW	14.22	31.99		
	Sigma Cell	9.67	27.44		
	1921 EW	17.40	35.17	1921 EW	0.05
	1921 EW	17.32	35.09	35.15	
	1921 EW	17.42	35.19		
	1921 LW	14.42	32.19	1921 LW	0.25
	1921 LW	14.82	32.59	32.48	
	1921 LW	14.89	32.66		
	1920 EW	15.78	33.55	1920 EW	0.20
	1920 EW	16.03	33.80	33.59	
	1920 EW	15.64	33.41		
VSU	Sample (6-20-03)				
017	Sigma Cell	9.74			
	Sigma Cell	9.45			
	Sigma Cell	9.63			
	1920 LW	14.69	32.46	1920 LW	
	1920 LW	14.32	32.09	32.17	0.26
	1920 LW	14.20	31.97		
	Sigma Cell	9.54	27.31		
	1919 EW	16.87	34.64	1919 EW	0.57
	1919 EW	17.70	35.47	34.83	
	1919 EW	16.61	34.38		
	1919 LW	14.56	32.33	1919 LW	0.52
	1919 LW	15.37	33.14	32.54	
	1919 LW	14.39	32.16		
	Sigma Cell	9.24	27.01		
	1918 EW	16.67	34.44	1918 EW	0.41
	1918 EW	16.13	33.90	34.35	
	1918 EW	16.93	34.70		
	Sigma Cell	9.43	27.20		
	1918 LW	15.57	33.34	1918 LW	0.38
	1918 LW	15.66	33.43	33.60	
	1918 LW	16.26	34.03		
	1917 EW	18.55	36.32	1917 EW	0.21
	1917 EW	18.36	36.13	36.33	
	1917 EW	18.78	36.55		
	1917 LW	17.08	34.85	1917 LW	0.10
	1917 LW	17.13	34.90	34.93	
	1917 LW	17.28	35.05		
	Sigma Cell	9.68	27.45		

	1916 EW	18.49	36.26	1916 EW	0.33
	1916 EW	18.11	35.88	35.92	
	1916 EW	17.84	35.61		
	1916 LW	15.58	33.35	1916 LW	0.22
	1916 LW	15.30	33.07	33.31	
	1916 LW	15.74	33.51		
	1915 EW	16.90	34.67	1915 EW	0.71
	1915 EW	17.98	35.75	35.47	
	1915 EW	18.23	36.00		
	1915 LW	15.69	33.46	1915 LW	0.74
	1915 LW	15.92	33.69	34.00	
	1915 LW	17.07	34.84		
	Sigma Cell	9.49	27.26		
	1914 EW	16.52	34.29	1914 EW	0.18
	1914 EW	16.29	34.06	34.26	
	1914 EW	16.65	34.42		
VSU	Sample (6-20b-03)				
017	SIGMA CELL	9.39			
	SIGMA CELL	9.52			
	SIGMA CELL	9.48			
	1914 LW	12.92	30.65	1914 LW	
	1914 LW	13.50	31.23	31.50	1.01
	1914 LW	14.89	32.62		
	1913 EW	19.50	37.23	1913 EW	
	1913 EW	18.99	36.72	36.65	0.62
	1913 EW	18.27	36.00		
	1913 LW	15.98	33.71	1913 LW	
	1913 LW	15.67	33.40	33.59	0.16
	1913 LW	15.92	33.65		
	SIGMA CELL	9.76	27.49		
	1912 EW	17.96	35.69	1912 EW	
	1912 EW	17.44	35.17	35.49	0.28
	1912 EW	17.87	35.60		
	1912 LW	15.71	33.44	1912 LW	
	1912 LW	15.91	33.64	33.31	0.41
	1912 LW	15.13	32.86		
	SIGMA CELL	9.51	27.24		
	1911 EW	19.48	37.21	1911 EW	
	1911 EW	18.93	36.66	36.95	0.28
	1911 EW	19.24	36.97		
	1911 LW	15.43	33.16	1911 LW	
	1911 LW	14.97	32.70	32.83	0.28
	1911 LW	14.91	32.64		

	1910 EW	19.19	36.92	1910 EW	
	1910 EW	18.66	36.39	36.53	0.35
	1910 EW	18.54	36.27		
	1910 LW	14.20	31.93	1910 LW	0.72
	1910 LW	15.11	32.84	32.71	
	1910 LW	15.62	33.35		
	SIGMA CELL	9.72	27.45		
	1909 EW	17.95	35.68	1909 EW	0.19
	1909 EW	17.96	35.69	35.57	
	1909 EW	17.62	35.35		
	1909 LW	Lost	Lost	1909 LW	0.49
	1909 LW	17.57	35.30	34.96	
	1909 LW	16.88	34.61		
	1908 EW	16.92	34.65	1908 EW	0.03
	1908 EW	16.87	34.60	34.61	
	1908 EW	16.86	34.59		
	1908 LW	16.63	34.36	1908 LW	0.57
	1908 LW	15.65	33.38	33.71	
	1908 LW	15.65	33.38		
	SIGMA CELL	9.64	27.37		

VSU	Sample (6-21-03)				
017	SIGMA CELL	9.11			
	SIGMA CELL	8.82			
	SIGMA CELL	8.91			
	1907 EW	16.38	35.06	1907 EW	0.45
	1907 EW	16.50	35.18	35.38	
	1907 EW	17.21	35.89		
	1907 LW	15.49	34.17	1907 LW	0.14
	1907 LW	15.22	33.90	34.05	
	1907 LW	15.40	34.08		
	SIGMA CELL	8.39	27.07		
	1906 EW	16.40	35.08	1906 EW	0.41
	1906 EW	16.77	35.45	35.06	
	1906 EW	15.96	34.64		
	1906 LW	13.45	32.13	1906 LW	0.39
	1906 LW	13.57	32.25	31.97	
	1906 LW	12.84	31.52		
	1905 EW	16.09	34.77	1905 EW	0.39
	1905 EW	15.32	34.00	34.37	
	1905 EW	15.67	34.35		
	1905 LW	13.79	32.47	1905 LW	0.22
	1905 LW	13.98	32.66	32.68	

	1905 LW	14.23	32.91		
	SIGMA CELL	8.52	27.20		
	1904 EW	17.98	36.66	1904 EW	0.37
	1904 EW	Lost	Lost	36.92	
	1904 EW	18.50	37.18		
	1904 LW	14.50	33.18	1904 LW	0.14
	1904 LW	14.77	33.45	33.30	
	1904 LW	14.60	33.28		
	1903 EW	14.71	33.39	1903 EW	0.35
	1903 EW	14.85	33.53	33.66	
	1903 EW	15.37	34.05		
	1903 LW	14.95	33.63	1903 LW	0.24
	1903 LW	Lost	Lost	33.46	
	1903 LW	14.61	33.29		
	SIGMA CELL	8.34	27.02		
	1902 EW	17.15	35.83	1902 EW	0.33
	1902 EW	16.54	35.22	35.60	
	1902 EW	17.07	35.75		
	1902 LW	13.03	31.71	1902 LW	0.01
	1902 LW	13.03	31.71	31.72	
	1902 LW	13.05	31.73		
	1901 EW	18.73	37.41	1901 EW	0.41
	1901 EW	18.98	37.66	37.31	
	1901 EW	18.18	36.86		
	SIGMA CELL	8.66	27.34		

VSU	Sample (6-22-03)				
017	Sigma Cell	8.92			
	Sigma Cell	8.30			
	Sigma Cell	8.63			
	1901 LW	13.47	32.30	1901 LW	0.18
	1901 LW	13.81	32.64	32.51	
	1901 LW	13.75	32.58		
	Sigma Cell	8.40	27.23		
	1900 EW	16.01	34.84	1900 EW	0.56
	1900 EW	15.01	33.84	34.49	
	1900 EW	15.95	34.78		
	1900 LW	14.42	33.25	1900 LW	0.26
	1900 LW	13.89	32.72	33.00	
	1900 LW	14.19	33.02		
	1899 EW	17.51	36.34	1899 EW	0.14
	1899 EW	17.25	36.08	36.17	
	1899 EW	17.27	36.10		

	1899 LW	14.60	33.43	1899 LW	0.36
	1899 LW	15.31	34.14	33.81	
	1899 LW	15.04	33.87		
	Sigma Cell	8.72	27.55		
	1898 EW	17.87	36.70	1898 EW	0.46
	1898 EW	17.22	36.05	36.57	
	1898 EW	18.12	36.95		
	Sigma Cell	8.82	27.65		
	1898 LW	13.98	32.81	1898 LW	0.20
	1898 LW	14.25	33.08	32.86	
	1898 LW	13.87	32.70		
	1897 EW	17.19	36.02	1897 EW	0.18
	1897 EW	16.83	35.66	35.83	
	1897 EW	16.97	35.80		
	1897 LW	15.06	33.89	1897 LW	0.43
	1897 LW	15.87	34.70	34.21	
	1897 LW	15.21	34.04		
	1896 EW	18.40	37.23	1896 EW	0.44
	1896 EW	19.06	37.89	37.73	
	1896 EW	19.24	38.07		
	1896 LW	15.11	33.94	1896 LW	0.37
	1896 LW	14.54	33.37	33.52	
	1896 LW	14.42	33.25		
	1895 EW	15.72	34.55	1895 EW	0.45
	1895 EW	15.81	34.64	34.86	
	1895 EW	16.54	35.37		
	1895 LW	14.92	33.75	1895 LW	0.14
	1895 LW	14.63	33.46	33.59	
	1895 LW	14.73	33.56		
	Sigma Cell	9.13	27.96		
VSU	Sample (6-22-03)				
017	Sigma Cell	9.50			
	Sigma Cell	9.22			
	Sigma Cell	8.91			
	1894 EW	17.06	35.12	1894 EW	0.21
	1894 EW	17.38	35.44	35.36	
	1894 EW	17.45	35.51		
	1894 LW	14.75	32.81	1894 LW	0.07
	1894 LW	14.75	32.81	32.85	
	1894 LW	14.88	32.94		
	1893 EW	17.87	35.93	1893 EW	0.03
	1893 EW	17.92	35.98	35.95	

	1893 EW	17.88	35.94		
	1893 LW	14.15	32.21	1893 LW	0.41
	1893 LW	14.00	32.06	32.36	
	1893 LW	14.76	32.82		
	Sigma Cell	9.35	27.41		
	1892 EW	19.58	37.64	1892 EW	0.22
	1892 EW	19.59	37.65	37.52	
	1892 EW	19.20	37.26		
	1892 TRew-lw	13.48	31.54	1892 TR	
	1892 TRew-lw	13.67	31.73	31.84	
	1892 TRew-lw	14.19	32.25		
	1892 LW	14.40	32.46	1892 LW	0.18
	1892 LW	14.03	32.09	32.28	
	1892 LW	14.21	32.27		
	1891 EW	18.24	36.30	1891 EW	0.28
	1891 EW	18.13	36.19	36.40	
	1891 EW	18.66	36.72		
	1891 TRew-lw	17.63	35.69	1891 TR	
	1891 TRew-lw	15.98	34.04	35.31	
	1891 TRew-lw	18.14	36.20		
	1891 LW	14.53	32.59	1891 LW	0.19
	1891 LW	14.56	32.62	32.71	
	1891 LW	14.87	32.93		
	1890 EW	17.30	35.36	1890 EW	0.43
	1890 EW	18.13	36.19	35.85	
	1890 EW	17.94	36.00		
	1890 LW	14.18	32.24	1890 LW	0.21
	1890 LW	14.29	32.35	32.41	
	1890 LW	14.59	32.65		
	Sigma Cell	9.45	27.51		
	1889 EW	16.54	34.60	1889 EW	0.35
	1889 EW	17.23	35.29	34.96	
	1889 EW	16.92	34.98		
	1889 LW	14.28	32.34	1889 LW	0.15
	1889 LW	14.58	32.64	32.52	
	1889 LW	14.51	32.57		
VSU	Sample (6-22b-03)				
017	SIGMA CELL	9.13			
	SIGMA CELL	9.12			
	SIGMA CELL	9.04			
	1888 EW	17.26	35.76	1888 EW	0.18
	1888 EW	17.57	36.07	35.97	
	1888 EW	17.58	36.08		

	1888 LW	13.04	31.54	1888 LW	0.37
	1888 LW	13.72	32.22	31.80	
	1888 LW	13.13	31.63		
	1887 EW	17.61	36.11	1887 EW	0.23
	1887 EW	17.36	35.86	35.87	
	1887 EW	17.14	35.64		
	1887 LW	15.56	34.06	1887 LW	0.24
	1887 LW	15.14	33.64	33.78	
	1887 LW	15.14	33.64		
	SIGMA CELL	8.59	27.09		
	1886 EW	17.75	36.25	1886 EW	0.18
	1886 EW	17.40	35.90	36.06	
	1886 EW	17.53	36.03		
	1886 LW	12.58	31.08	1886 LW	0.30
	1886 LW	12.76	31.26	31.34	
	1886 LW	13.17	31.67		
	1885 EW	16.14	34.64	1885 EW	0.20
	1885 EW	16.43	34.93	34.78	
	1885 EW	Lost	Lost		
	1885 LW	14.96	33.46	1885 LW	1.05
	1885 LW	13.62	32.12	32.33	
	1885 LW	12.90	31.40		
	SIGMA CELL	8.66	27.16		
	1884 EW	16.00	34.50	1884 EW	0.14
	1884 EW	15.73	34.23	34.35	
	1884 EW	15.82	34.32		
	SIGMA CELL	8.43	26.93		
	1884 LW	12.75	31.25	1884 LW	1.00
	1884 LW	13.06	31.56	31.97	
	1884 LW	14.62	33.12		
	1883 EW	15.53	34.03	1883 EW	0.03
	1883 EW	15.59	34.09	34.06	
	1883 EW	15.55	34.05		
	1883 LW	13.50	32.00	1883 LW	0.17
	1883 LW	13.70	32.20	32.18	
	1883 LW	13.84	32.34		
	1882 EW	16.18	34.68	1882 EW	0.63
	1882 EW	16.29	34.79	34.38	
	1882 EW	15.15	33.65		
	SIGMA CELL	8.66	27.16		

VSU	Sample (6-22b-03)	
017	SIGMA CELL	8.94

	1882 ELW	13.82	32.50	1882 ELW	0.27
	1882 ELW	13.68	32.36	32.58	
	1882 ELW	14.20	32.88		
	1882 LLW	13.70	32.38	1882 LLW	0.17
	1882 LLW	13.98	32.66	32.57	
	1882 LLW	14.01	32.69		
	SIGMA CELL	8.39	27.07		
	1881 EW	Lost	Lost	1881 EW	0.84
	1881 EW	15.96	34.64	34.04	
	1881 EW	14.77	33.45		
	1881 ELW	13.56	32.24	1881 ELW	0.24
	1881 ELW	13.93	32.61	32.51	
	1881 ELW	14.01	32.69		
	1881 LLW	14.12	32.80	1881 LLW	0.15
	1881 LLW	14.43	33.11	32.95	
	1881 LLW	14.24	32.92		
	1880 EW	14.90	33.58	1880 EW	0.18
	1880 EW	15.23	33.91	33.69	
	1880 EW	14.92	33.60		
	1880 LW	12.27	30.95	1880 LW	0.28
	1880 LW	12.70	31.38	31.26	
	1880 LW	12.78	31.46		
	SIGMA CELL	Lost	Lost		
	1879 EW	Lost	Lost	1879 EW	0.36
	1879 EW	16.50	35.18	35.43	
	1879 EW	17.00	35.68		
	1879 ELW	12.81	31.49	1879 ELW	0.28
	1879 ELW	12.88	31.56	31.36	
	1879 ELW	12.36	31.04		
	1879 LLW	11.82	30.50	1879 LLW	0.44
	1879 LLW	12.06	30.74	30.37	
	1879 LLW	11.20	29.88		
VSU	Sample (6-22b-03)				
017	SIGMA CELL	8.69			
	SIGMA CELL	8.84			
	1878 EW	15.77	34.44	1878 EW	0.08
	1878 EW	15.80	34.47	34.41	
	1878 EW	15.65	34.32		
	1878 ELW	13.29	31.96	1878 ELW	0.33
	1878 ELW	12.64	31.31	31.62	
	1878 ELW	12.91	31.58		
	1878 LLW	13.81	32.48	1878 LLW	
	1878 LLW	12.01	30.68	31.01	1.34

	1878 LLW	11.20	29.87		
	SIGMA CELL	8.58	27.25		
VSU	Sample (6-24-03)	Raw Nos			
017	sigma cell	8.81			
	sigma cell	8.29			
	sigma cell	8.48			
	1877 EW	15.52	34.45	1877 EW	0.33
	1877 EW	15.25	34.18	34.49	
	1877 EW	15.91	34.84		
	1877 ELW	11.83	30.76	1877 ELW	0.16
	1877 ELW	12.12	31.05	30.94	
	1877 ELW	12.08	31.01		
	1877 LLW	12.29	31.22	1877 LLW	0.19
	1877 LLW	12.29	31.22	31.11	
	1877 LLW	11.96	30.89		
	sigma cell	8.06	26.99		
	1876 EW	17.42	36.35	1876 EW	0.16
	1876 EW	17.31	36.24	36.21	
	1876 EW	17.11	36.04		
	1876 LW	13.72	32.65	1876 LW	0.04
	1876 LW	13.79	32.72	32.70	
	1876 LW	13.80	32.73		
	1875 EW	17.20	36.13	1875 EW	0.31
	1875 EW	16.90	35.83	36.14	
	1875 EW	17.52	36.45		
	1875 LW	14.32	33.25	1875 LW	0.27
	1875 LW	13.78	32.71	32.98	
	1875 LW	14.06	32.99		
	1874 EW	14.98	33.91	1874 EW	0.28
	1874 EW	15.54	34.47	34.18	
	1874 EW	15.22	34.15		
	1874 LW	13.20	32.13	1874 LW	0.33
	1874 LW	13.28	32.21	31.98	
	1874 LW	12.68	31.61		
VSU	Sample (6-25-03)				
017	sigma cell	8.79			
	sigma cell	8.76			
	sigma cell	8.99			
	1873 EW	17.10	35.45	1873 EW	0.91
	1873 EW	18.89	37.24	36.25	
	1873 EW	17.73	36.08		

	1873 ELW	12.92	31.27	1873 ELW	0.21
	1873 ELW	13.29	31.64	31.39	
	1873 ELW	12.91	31.26		
	1873 LLW	14.40	32.75	1873 LLW	1.12
	1873 LLW	14.84	33.19	33.60	
	1873 LLW	16.52	34.87		
	1872 EW	16.46	34.81	1872 EW	0.56
	1872 EW	15.34	33.69	34.23	
	1872 EW	15.85	34.20		
	sigma cell	9.08	27.43		
	1872 ELW	13.57	31.92	1872 ELW	0.05
	1872 ELW	13.57	31.92	31.95	
	1872 ELW	13.66	32.01		
	1872 LLW	15.64	33.99	1872 LLW	0.21
	1872 LLW	15.78	34.13	33.94	
	1872 LLW	15.36	33.71		
	sigma cell	8.11	26.46		
	1871 EW	14.93	33.28	1871 EW	0.47
	1871 EW	15.35	33.70	33.73	
	1871 EW	15.86	34.21		
	1871 ELW	12.27	30.62	1871 ELW	0.37
	1871 ELW	12.38	30.73	30.89	
	1871 ELW	12.96	31.31		
	1871 MLW	11.90	30.25	1871 MLW	0.35
	1871 MLW	11.39	29.74	30.14	
	1871 MLW	12.07	30.42		
	1871 LLW	13.57	31.92	1871 LLW	0.10
	1871 LLW	13.38	31.73	31.82	
	1871 LLW	13.46	31.81		
	1870 EW	17.91	36.26	1870 EW	0.24
	1870 EW	17.54	35.89	35.98	
	1870 EW	17.45	35.80		
	1870 LW	13.99	32.34	1870 LW	0.03
	1870 LW	13.99	32.34	35.98	
	1870 LW	13.94	32.29		
	sigma cell	8.70	27.05		
	1869 EW	16.13	34.48	1869 EW	0.23
	1869 EW	16.59	34.94	34.73	
	1869 EW	16.42	34.77		

VSU	Sample (6-25b-03)	
017	SIGMA	8.79
	SIGMA	8.83
	SIGMA	8.78

1869 LW	14.00	32.71	1869 LW	0.73
1869 LW	13.74	32.45	32.99	
1869 LW	15.11	33.82		
1868 EW	15.60	34.31	1868 EW	0.53
1868 EW	16.01	34.72	34.79	
1868 EW	16.65	35.36		
1868 ELW	11.94	30.65	1868 ELW	0.28
1868 ELW	12.16	30.87	30.90	
1868 ELW	12.49	31.20		
1868 LLW	13.84	32.55	1868 LLW	0.29
1868 LLW	14.27	32.98	32.65	
1868 LLW	13.71	32.42		
SIGMA	8.46	27.17		
1867 EW	15.35	34.06	1867 EW	
1867 EW	15.54	34.25	34.26	
1867 EW	15.74	34.45		
1867 ELW	12.00	30.71	1867 ELW	
1867 ELW	12.47	31.18	30.92	
1867 ELW	12.16	30.87		
1867 LLW	13.11	31.82	1867 LLW	0.37
1867 LLW	12.75	31.46	31.45	
1867 LLW	12.37	31.08		
1866 EW	15.68	34.39	1866 EW	0.01
1866 EW	15.70	34.41	34.40	
1866 EW	15.68	34.39		
1866 LW	14.97	33.68	1866 LW	0.02
1866 LW	14.95	33.66	33.65	
1866 LW	14.92	33.63		
SIGMA	8.74	27.45		
1865 EW	17.54	36.25	1865 EW	0.24
1865 EW	17.92	36.63	36.52	
1865 EW	17.98	36.69		
1865 ELW	13.94	32.65	1865 ELW	0.23
1865 ELW	14.37	33.08	32.91	
1865 ELW	14.27	32.98		
1865 LLW	14.31	33.02	1865 LLW	0.23
1865 LLW	13.94	32.65	32.91	
1865 LLW	14.36	33.07		
1864 EW	17.69	36.40	1864 EW	0.30
1864 EW	18.11	36.82	36.73	
1864 EW	18.25	36.96		
1864 LW	14.83	33.54	1864 LW	
1864 LW	13.74	32.45	32.98	
1864 LW	14.24	32.95		

VSU	Sample (6-26-03)				
017	sigma cell	9.48			
	sigma cell	9.44			
	sigma cell	9.65			
	1863 EW	17.72	35.57	1863 EW	0.35
	1863 EW	18.13	35.98	35.93	
	1863 EW	18.41	36.26		
	1863 LW	15.21	33.06	1863 LW	0.18
	1863 LW	14.86	32.71	32.86	
	1863 LW	14.98	32.83		
	1862 EW	18.04	35.89	1862 EW	0.48
	1862 EW	17.21	35.06	35.61	
	1862 EW	18.04	35.89		
	1862 LW	14.62	32.47	1862 LW	0.18
	1862 LW	14.27	32.12	32.31	
	1862 LW	14.49	32.34		
	Sigma Cell	9.46	27.31		
	1861 EW	17.73	35.58	1861 EW	0.08
	1861 EW	17.89	35.74	35.64	
	1861 EW	17.76	35.61		
	1861 LW	14.57	32.42	1861 LW	0.23
	1861 LW	15.00	32.85	32.69	
	1861 LW	14.96	32.81		
	sigma cell	9.56	27.41		
	1860 EW	18.62	36.47	1860 EW	0.23
	1860 EW	18.63	36.48	36.60	
	1860 EW	19.02	36.87		
	1860 LW	16.37	34.22	1860 LW	0.26
	1860 LW	15.86	33.71	33.98	
	1860 LW	16.17	34.02		
	1859 EW	17.59	35.44	1859 EW	
	1859 EW	17.89	35.74	35.65	
	1859 EW	17.91	35.76		
	1859 ELW	13.97	31.82	1859 ELW	0.24
	1859 ELW	14.10	31.95	32.02	
	1859 ELW	14.44	32.29		
	1859 LLW	15.49	33.34	1859 LLW	0.49
	1859 LLW	14.61	32.46	33.03	
	1859 LLW	15.44	33.29		
	sigma cell	9.53	27.38		
	1858 EW	18.62	36.47	1858 EW	0.06
	1858 EW	18.54	36.39	36.40	
	1858 EW	18.49	36.34		

	1858 ELW	14.04	31.89	1858 ELW	0.30
	1858 ELW	14.20	32.05	32.14	
	1858 ELW	14.62	32.47		
VSU	Sample (6-26B-03)				
017	Sigma Cell	9.31			
	Sigma Cell	9.40			
	Sigma Cell	8.86			
	1858 LLW	13.00	31.17	1858 LLW	0.12
	1858 LLW	13.03	31.20	31.25	
	1858 LLW	13.21	31.38		
	1857 EW	17.18	35.35	1857 EW	0.87
	1857 EW	18.25	36.42	35.49	
	1857 EW	16.53	34.70		
	1857 ELW	12.28	30.45	1857 ELW	0.34
	1857 ELW	12.91	31.08	30.70	
	1857 ELW	12.39	30.56		
	1857 MLW	14.52	32.69	1857 MLW	0.53
	1857 MLW	14.66	32.83	32.46	
	1857 MLW	13.69	31.86		
	1857 LLW	15.53	33.70	1857 LLW	0.13
	1857 LLW	15.78	33.95	33.85	
	1857 LLW	15.73	33.90		
	Sigma Cell	9.16	27.33		
	1856 EW	17.45	35.62	1856 EW	0.18
	1856 EW	17.61	35.78	35.79	
	1856 EW	17.80	35.97		
	1856 ELW	14.32	32.49	1856 ELW	0.10
	1856 ELW	14.37	32.54	32.57	
	1856 ELW	14.51	32.68		
	1856 MLW	15.05	33.22	1856 MLW	0.30
	1856 MLW	15.42	33.59	33.27	
	1856 MLW	14.83	33.00		
	1856 LLW	16.94	35.11	1856 LLW	0.28
	1856 LLW	16.88	35.05	34.92	
	1856 LLW	16.42	34.59		
	Sigma Cell	9.13	27.30		
	1855 EW	18.81	36.98	1855 EW	0.32
	1855 EW	18.78	36.95	36.78	
	1855 EW	18.25	36.42		
	1855 LW	14.70	32.87	1855 LW	0.39
	1855 LW	15.32	33.49	33.04	
	1855 LW	14.59	32.76		
	1854 EW	16.98	35.15	1854 EW	0.16

	1854 EW	16.69	34.86	34.97	
	1854 EW	16.74	34.91		
	1854 LW	14.94	33.11	1854 LW	0.39
	1854 LW	14.40	32.57	32.68	
	1854 LW	14.18	32.35		
	Sigma Cell	8.89	27.06		
VSU	Sample (6-27-03)				
017	sigma cell	8.90			
	sigma cell	8.63			
	sigma cell	8.93			
	1853 EW	16.86	35.56	1853 EW	0.31
	1853 EW	17.41	36.11	35.75	
	1853 EW	16.90	35.60		
	1853 LW	12.48	31.18	1853 LW	0.57
	1853 LW	12.80	31.50	31.66	
	1853 LW	13.59	32.29		
	1852 EW	15.50	34.20	1852 EW	0.65
	1852 EW	15.63	34.33	34.64	
	1852 EW	16.68	35.38		
	1852 ELW	11.30	30.00	1852 ELW	0.24
	1852 ELW	11.77	30.47	30.22	
	1852 ELW	11.51	30.21		
	1852 LLW	12.92	31.62	1852 LLW	0.23
	1852 LLW	13.21	31.91	31.87	
	1852 LLW	13.37	32.07		
	sigma cell	8.45	27.15		
	1851 EW	17.42	36.12	1851 EW	0.35
	1851 EW	17.99	36.69	36.52	
	1851 EW	18.06	36.76		
	1851 ELW	13.23	31.93	1851 ELW	0.06
	1851 ELW	13.33	32.03	31.96	
	1851 ELW	13.23	31.93		
	1851 MLW	14.03	32.73	1851 MLW	0.16
	1851 MLW	14.15	32.85	32.87	
	1851 MLW	14.35	33.05		
	1851 LLW	14.42	33.12	1851 LLW	0.18
	1851 LLW	14.52	33.22	33.27	
	1851 LLW	14.77	33.47		
	sigma cell	8.87	27.57		
	1850 EW	16.48	35.18	1850 EW	0.19
	1850 EW	16.51	35.21	35.30	
	1850 EW	16.82	35.52		
	1850 LW	14.85	33.55	1850 LW	0.60

	1850 LW	14.49	33.19	33.70	
	1850 LW	15.65	34.35		
	sigma cell	8.63	27.33		
	1849 EW	16.05	34.75	1849 EW	0.41
	1849 EW	15.50	34.20	34.65	
	1849 EW	16.31	35.01		
	1849 LW	14.12	32.82	1849 LW	0.55
	1849 LW	13.18	31.88	32.18	
	1849 LW	13.15	31.85		
	sigma cell	8.87	27.57		
VSU	Sample (6-28-03)				
017	SIGMA	10.00			
	SIGMA	9.94			
	SIGMA	9.78			
	1848 EW	17.30	34.73	1848 EW	0.08
	1848 EW	17.21	34.64	34.73	
	1848 EW	17.37	34.80		
	1848 LW	14.94	32.37	1848 LW	0.36
	1848 LW	Lost	Lost	32.11	
	1848 LW	14.43	31.86		
	SIGMA	9.91	27.34		
	1847 EW	16.28	33.71	1847 EW	0.30
	1847 EW	16.81	34.24	33.89	
	1847 EW	16.30	33.73		
	1847 ELW	11.35	28.78	1847 ELW	0.58
	1847 ELW	12.47	29.90	29.26	
	1847 ELW	11.68	29.11		
	1847 LLW	13.06	30.49	1847 LLW	0.72
	1847 LLW	11.68	29.11	29.68	
	1847 LLW	12.00	29.43		
	SIGMA	9.29	26.72		
	1846 EW	16.59	34.02	1846 EW	0.42
	1846 EW	15.76	33.19	33.55	
	1846 EW	16.00	33.43		
	1846 ELW	11.58	29.01	1846 ELW	0.79
	1846 ELW	12.26	29.69	29.76	
	1846 ELW	13.16	30.59		
	1846 LLW	10.50	27.93	1846 LLW	0.70
	1846 LLW	11.69	29.12	28.73	
	1846 LLW	11.71	29.14		
	SIGMA	9.37	26.80		
	1845 EW	Lost	Lost	1845 EW	0.27

	1845 EW	16.05	33.48	33.67	
	1845 EW	16.43	33.86		
	1845 ELW	15.78	33.21	1845 ELW	0.30
	1845 ELW	15.62	33.05	32.97	
	1845 ELW	15.20	32.63		
	1845 LLW	14.80	32.23	1845 LLW	0.66
	1845 LLW	15.01	32.44	31.96	
	1845 LLW	13.78	31.21		
	SIGMA	9.41	26.84		
	1844 EW	17.39	34.82	1844 EW	0.09
	1844 EW	17.32	34.75	34.74	
	1844 EW	17.21	34.64		
	1844 ELW	13.32	30.75	1844 ELW	0.17
	1844 ELW	13.65	31.08	30.91	
	1844 ELW	13.47	30.90		
VSU	Sample (6-28-03)				
017	SIGMA	9.66			
	SIGMA	9.58			
	SIGMA	9.74			
	1844 LLW	13.91	31.59	1844 LLW	0.38
	1844 LLW	13.18	30.86	31.29	
	1844 LLW	13.74	31.42		
	SIGMA	9.64	27.32		
	1843 EW	16.63	34.31	1843 EW	0.27
	1843 EW	17.16	34.84	34.58	
	1843 EW	16.90	34.58		
	1843 ELW	13.07	30.75	1843 ELW	0.12
	1843 ELW	12.86	30.54	30.61	
	1843 ELW	12.86	30.54		
	1843 LLW	13.86	31.54	1843 LLW	0.37
	1843 LLW	14.40	32.08	31.67	
	1843 LLW	13.70	31.38		
	SIGMA	9.56	27.24		
	1842 EW	16.55	34.23	1842 EW	0.18
	1842 EW	16.35	34.03	34.05	
	1842 EW	16.19	33.87		
	1842 LW	14.23	31.91	1842 LW	0.19
	1842 LW	14.35	32.03	31.86	
	1842 LW	13.98	31.66		
	1841 EW	16.95	34.63	1841 EW	0.18
	1841 EW	17.04	34.72	34.78	
	1841 EW	17.30	34.98		

	1841 LW	13.13	30.81	1841 LW	0.36
	1841 LW	13.39	31.07	30.75	
	1841 LW	12.69	30.37		
	SIGMA	9.48	27.16		
	1840 EW	12.75	30.43	1840 EW	0.39
	1840 EW	12.61	30.29	30.58	
	1840 EW	13.35	31.03		
	1840 LW	13.07	30.75	1840 LW	0.53
	1840 LW	13.26	30.94	31.15	
	1840 LW	14.07	31.75		
VSU	Sample (8/28/03)				
017	sigma cell	9.24			
	sigma cell	9.00			
	sigma cell	9.16			
	sigma cell	9.17			
	sigma cell	9.41			
	1970 EW	13.27	31.44	1970 EW	
	1970 EW	13.28	31.45	31.36	0.14
	1970 EW	13.03	31.20		
	1970 LW	14.42	32.58	1970 LW	
	1970 LW	14.75	32.92	32.73	0.17
	1970 LW	14.51	32.68		
	sigma cell	9.34	27.51		
	1971 EW	15.07	32.96	1971 EW	
	1971 EW	15.47	33.37	33.06	0.25
	1971 EW	15.52	33.42		
	1971 LW	14.59	32.49	1971 LW	
	1971 LW	14.93	32.83	32.75	0.22
	1971 LW	15.02	32.92		
	sigma cell	9.64	27.54		
	1972 EW	14.99	32.74	1972 EW	
	1972 EW	14.62	32.37	32.46	0.24
	1972 EW	14.54	32.29		
	1972 LW	14.11	31.86	1972 LW	
	1972 LW	14.29	32.04	32.07	0.22
	1972 LW	14.55	32.30		
	sigma cell	9.50	27.24		
	1973 EW	15.96	33.75	1973 EW	0.37
	1973 EW	15.22	33.02	33.42	
	1973 EW	15.69	33.49		
	1973 LW	15.57	33.36	1973 LW	0.28
	1973 LW	15.01	32.81	33.08	
	1973 LW	15.26	33.06		

	sigma cell	9.63	27.43		
	1974 EW	17.13	34.85	1974 EW	
	1974 EW	16.06	33.78	34.37	0.54
	1974 EW	16.74	34.46		
	1974 LW	15.56	33.28	1974 LW	
	1974 LW	14.84	32.57	33.01	0.39
	1974 LW	15.46	33.19		
	sigma cell	9.60	27.32		
	1975 EW	14.97	32.66	1975 EW	
	1975 EW	15.70	33.39	33.30	0.60
	1975 EW	16.16	33.85		
	sigma cell	9.90	27.59		
LL029B	Sample (11-10-03)				STD
029B					
	Sigma Cell	8.39	27.52		
	Sigma Cell	8.55	27.68		
	Sigma Cell	8.09	27.22		
	Sigma Cell	7.97	27.10		
	Sigma Cell	8.34	27.47		
	Sigma Cell	8.01	27.14		
	Sigma Cell	8.33	27.46		
	Sigma Cell	7.96	27.09		
	1845 EW	15.56	34.69	1845 EW	
	1845 EW	15.85	34.98	34.91	0.20
	1845 EW	15.95	35.08		
	1845 LW	14.94	34.07	1845 LW	
	1845 LW	15.33	34.46	34.91	0.20
	1845 LW	15.03	34.16		
	1844 EW	16.73	35.86	1844 EW	
	1844 EW	16.39	35.52	35.82	0.28
	1844 EW	16.94	36.07		
	1844 LW	12.35	31.48	1844 LW	
	1844 LW	12.35	31.48	31.61	0.22
	1844 LW	12.74	31.87		
	Sigma Cell	8.19	27.32		
	1843 EW	16.17	35.35	1843 EW	
	1843 EW	16.37	35.55	35.46	0.10
	1843 EW	16.30	35.47		
	1843 LW	13.32	32.49	1843 LW	
	1843 LW	13.33	32.51	32.36	0.25
	1843 LW	12.89	32.07		

	Sigma Cell	8.10	27.28		
	1842 EW	15.68	34.91	1842 EW	
	1842 EW	15.56	34.79	34.84	0.06
	1842 EW	15.59	34.82		
	1842 LW	13.03	32.26	1842 LW	
	1842 LW	12.79	32.02	32.21	0.17
	1842 LW	13.12	32.35		
	Sigma Cell	8.18	27.41		
	1841 EW	15.83	34.94	1841 EW	
	1841 EW	15.64	34.75	34.97	0.23
	1841 EW	16.10	35.21		
	1841 LW	12.87	31.98	1841 LW	
	1841 LW	13.29	32.40	32.16	0.22
	1841 LW	12.99	32.10		
	Sigma Cell	8.33	27.44		
	1840 EW	16.65	35.76	1840 EW	
	1840 EW	15.80	34.91	35.18	0.50
	1840 EW	15.76	34.87		
LL029B	Sample (11-10-03)				STD
	Sigma Cell	8.00	27.00		
	Sigma Cell	8.07	27.07		
	Sigma Cell	8.14	27.14		
	1840 LW	13.52	32.52	1840 LW	
	1840 LW	13.66	32.66	32.60	0.08
	1840 LW	13.64	32.64		
	Sigma Cell	8.38	27.38		
	1839 EW	15.27	34.17	1839 EW	
	1839 EW	15.53	34.43	34.22	0.19
	1839 EW	15.15	34.05		
	1839 LW	13.75	32.66	1839 LW	
	1839 LW	bad	Bad No	32.82	0.24
	1839 LW	14.09	32.99		
	Sigma Cell	8.46	27.36		
	1838 EW	14.95	34.04	1838 EW	
	1838 EW	15.20	34.29	34.22	0.16
	1838 EW	15.25	34.33		
	1838 LW	12.96	32.05	1838 LW	
	1838 LW	13.02	32.11	32.16	0.14
	1838 LW	13.22	32.31		
	Sigma Cell	8.15	27.24		
	1837 EW	16.84	35.88	1837 EW	

	1837 EW	17.00	36.04	35.86	0.20
	1837 EW	16.61	35.65		
	1837 LW	14.16	33.20	1837 LW	
	1837 LW	14.20	33.24	33.10	0.20
	1837 LW	13.84	32.88		
	Sigma Cell	8.45	27.49		
	1836 EW	17.66	36.61	1836 EW	
	1836 EW	17.74	36.69	36.66	0.04
	1836 EW	17.71	36.67		
	1836 LW	14.37	33.32	1836 LW	
	1836 LW	13.95	32.91	33.06	0.23
	1836 LW	14.01	32.96		
	Sigma Cell	8.32	27.28		
	1835 EW	15.80	34.82	1835 EW	
	1835 EW	15.67	34.69	34.70	0.12
	1835 EW	15.56	34.58		
	1835 LW	14.24	33.26	1835 LW	
	1835 LW	14.19	33.21	33.43	0.33
	1835 LW	14.78	33.80		
	Sigma Cell	8.31	27.34		
	1834 EW	16.68	35.70	1834 EW	
	1834 EW	16.28	35.30	35.55	0.21
	1834 EW	16.61	35.64		
LL029B	Sample (11-10-03)				
	Sigma Cell	8.61			
	Sigma Cell	8.85			
	Sigma Cell	8.61			
	Sigma Cell	8.60			
	1834 LW	13.93	32.64	1834 LW	
	1834 LW	13.50	32.21	32.26	0.36
	1834 LW	13.21	31.92		
	Sigma Cell	8.59	27.30		
	1833 EW	17.45	36.10	1833 EW	
	1833 EW	17.01	35.67	35.90	0.22
	1833 EW	17.29	35.95		
	1833 LW	16.57	35.22	1833 LW	
	1833 LW	15.50	34.15	34.94	0.70
	1833 LW	16.82	35.47		
	Sigma Cell	8.79	27.44		
	1832 EW	17.17	35.86	1832 EW	
	1832 EW	16.59	35.29	35.52	0.31
	1832 EW	16.70	35.40		
	1832 LW	14.45	33.14	1832 LW	

	1832 LW	14.49	33.19	33.16	0.03
	1832 LW	14.44	33.13		
	Sigma Cell	8.51	27.20		
	1831 EW	15.60	34.42	1831 EW	
	1831 EW	15.40	34.22	34.39	0.16
	1831 EW	15.70	34.53		
	1831 LW	13.64	32.46	1831 LW	
	1831 LW	13.78	32.61	32.57	0.10
	1831 LW	13.84	32.66		
	Sigma Cell	8.53	27.35		
	1830 EW	17.07	35.81	1830 EW	
	1830 EW	17.07	35.81	35.50	0.54
	1830 EW	16.14	34.88		
	1830 LW	13.60	32.34	1830 LW	
	1830 LW	13.10	31.84	32.09	0.25
	1830 LW	13.35	32.09		
	Sigma Cell	8.67	27.41		
	1829 EW	17.42	36.02	1829 EW	
	1829 EW	16.59	35.19	35.70	0.44
	1829 EW	17.29	35.89		
	1829 LW	13.50	32.10	1829 LW	
	1829 LW	12.83	31.43	31.97	0.49
	1829 LW	13.79	32.39		
	Sigma Cell	8.82	27.41		
	1828 EW	17.19	35.79	1828 EW	
	1828 EW	17.08	35.68	35.73	0.05
	1828 EW	17.12	35.72		
LL029B	Sample (11-10-03)				STD
	Sigma Cell	7.91			
	Sigma Cell	7.91			
	Sigma Cell	8.04		1828 LW	
	1828 LW	13.92	33.07	32.92	0.24
	1828 LW	13.51	32.65		
	1828 LW	13.91	33.05		
	Sigma Cell	8.44	27.58		
	1827 EW	15.66	34.65	1827 EW	
	1827 EW	15.26	34.25	34.49	0.21
	1827 EW	15.57	34.57		
	1827 LW	12.06	31.06	1827 LW	
	1827 LW	11.74	30.73	30.83	0.20
	1827 LW	11.70	30.69		
	Sigma Cell	8.25	27.25		

	1826 EW	16.83	36.07	1826 EW	
	1826 EW	17.34	36.57	36.27	0.27
	1826 EW	16.93	36.17		
	1826 LW	14.67	33.91	1826 LW	
	1826 LW	14.25	33.48	33.66	0.22
	1826 LW	14.37	33.60		
	Sigma Cell	7.96	27.20		
	1825 EW	17.03	36.25	1825 EW	
	1825 EW	17.44	36.66	36.44	0.21
	1825 EW	17.18	36.40		
	1825 LW	14.66	33.88	1825 LW	
	1825 LW	14.38	33.60	33.84	0.23
	1825 LW	14.83	34.05		
	Sigma Cell	8.28	27.50		
	1824 EW	16.68	35.78	1824 EW	
	1824 EW	17.66	36.76	36.20	0.50
	1824 EW	16.98	36.07		
	1824 LW	15.15	34.24	1824 LW	
	1824 LW	15.72	34.82	34.46	0.31
	1824 LW	15.23	34.33		
	Sigma Cell	8.21	27.30		
	1823 EW	17.54	36.56	1823 EW	
	1823 EW	17.76	36.78	36.65	0.12
	1823 EW	17.58	36.60		
	1823 LW	13.01	32.03	1823 LW	
	1823 LW	13.56	32.57	32.51	0.45
	1823 LW	13.90	32.92		
	Sigma Cell	8.44	27.46		
	1822 EW	16.20	35.17	1822 EW	
	1822 EW	16.70	35.67	35.53	0.31
	1822 EW	16.78	35.75		
	1822 LW	12.91	31.88	1822 LW	
	1822 LW	14.77	33.73	32.71	0.94
	1822 LW	13.55	32.52		
	Sigma Cell	8.30	27.27		
LL029B	Sample (11-10-03)				STD
	Sigma Cell	8.52			
	Sigma Cell	8.50			
	Sigma Cell	8.30			
	1821 EW	15.22	34.28	1821 EW	
	1821 EW	15.41	34.47	34.49	0.22
	1821 EW	15.66	34.72		

	1821 LW	12.17	31.23	1821 LW	
	1821 LW	11.99	31.05	31.21	0.15
	1821 LW	12.29	31.35		
	Sigma Cell	8.12	27.18		
	1820 EW	14.04	33.13	1820 EW	
	1820 EW	14.23	33.31	33.05	0.31
	1820 EW	13.62	32.71		
	1820 LW	13.76	32.84	1820 LW	
	1820 LW	13.11	32.19	32.58	0.34
	1820 LW	13.62	32.70		
	Sigma Cell	8.39	27.47		
	1819 EW	15.48	34.55	1819 EW	
	1819 EW	13.79	32.86	33.90	0.91
	1819 EW	15.21	34.29		
	1819 LW	12.34	31.41	1819 LW	
	1819 LW	12.28	31.36	31.27	0.21
	1819 LW	11.95	31.03		
	Sigma Cell	8.14	27.21		
	1818 EW	16.23	35.35	1818 EW	
	1818 EW	16.01	35.13	35.27	0.13
	1818 EW	16.22	35.34		
	1818 LW	13.63	32.75	1818 LW	
	1818 LW	14.04	33.15	32.97	0.21
	1818 LW	13.88	33.00		
	Sigma Cell	8.31	27.43		
	1817 EW	16.05	34.98	1817 EW	
	1817 EW	16.58	35.51	35.28	0.28
	1817 EW	16.44	35.37		
	1817 LW	14.74	33.67	1817 LW	
	1817 LW	14.84	33.76	33.56	0.27
	1817 LW	14.33	33.26		
	Sigma Cell	8.52	27.45		
	1816 EW	16.94	35.77	1816 EW	
	1816 EW	16.68	35.51	35.61	0.14
	1816 EW	16.71	35.54		
	1816 LW	14.44	33.27	1816 LW	
	1816 LW	14.23	33.06	33.19	0.11
	1816 LW	14.42	33.24		
	Sigma Cell	8.51	27.34		
LL029B	Sample (11-10-03)				STD
	Sigma Cell	7.28			
	Sigma Cell	6.80			

Sigma Cell	6.69			
1815 EW	13.53	34.04	1815 EW	
1815 EW	13.50	34.01	33.97	0.10
1815 EW	13.35	33.86		
1815 LW	11.71	32.22	1815 LW	
1815 LW	11.56	32.07	32.10	0.11
1815 LW	11.50	32.01		
Sigma Cell	6.74	27.25		
1814 EW	14.67	35.34	1814 EW	
1814 EW	14.78	35.46	35.36	0.09
1814 EW	14.62	35.29		
1814 LW	13.31	33.98	1814 LW	
1814 LW	13.34	34.01	33.87	0.22
1814 LW	12.95	33.62		
Sigma Cell	6.60	27.27		
1813 EW	13.85	34.63	1813 EW	
1813 EW	13.07	33.85	34.06	0.49
1813 EW	12.95	33.72		
1813 LW	10.03	30.80	1813 LW	
1813 LW	10.12	30.90	30.97	0.22
1813 LW	10.44	31.21		
Sigma Cell	6.54	27.31		
1812 EW	13.79	34.48	1812 EW	
1812 EW	13.26	33.96	34.19	0.27
1812 EW	13.42	34.12		
1812 LW	10.66	31.36	1812 LW	
1812 LW	10.25	30.95	31.21	0.22
1812 LW	10.61	31.30		
Sigma Cell	6.74	27.44		
1811 EW	13.67	34.13	1811 EW	
1811 EW	13.56	34.02	33.88	0.34
1811 EW	13.03	33.49		
1811 LW	10.35	30.81	1811 LW	
1811 LW	11.01	31.47	31.16	0.33
1811 LW	10.73	31.19		
Sigma Cell	7.02	27.48		
1810 EW	13.07	33.42	1810 EW	
1810 EW	13.03	33.38	33.63	0.39
1810 EW	13.72	34.07		
1810 LW	11.11	31.47	1810 LW	
1810 LW	11.56	31.91	31.80	0.29
1810 LW	11.66	32.01		
Sigma Cell	6.96	27.31		

LL029B	Sample (11-10-03)				STD
	Sigma Cell	6.71			
	Sigma Cell	6.79			
	Sigma Cell	6.13			
	1809 EW	13.00	33.76	1809 EW	
	1809 EW	13.19	33.95	33.90	0.12
	1809 EW	13.23	33.99		
	1809 LW	10.29	31.05	1809 LW	
	1809 LW	10.58	31.34	31.20	0.14
	1809 LW	10.46	31.22		
	Sigma Cell	6.68	27.44		
	1808 EW	15.55	36.17	1808 EW	
	1808 EW	15.51	36.14	36.15	0.02
	1808 EW	15.53	36.15		
	1808 LW	12.55	33.17	1808 LW	
	1808 LW	12.52	33.14	33.09	0.11
	1808 LW	12.34	32.96		
	Sigma Cell	6.76	27.38		
	1807 EW	13.71	34.35	1807 EW	
	1807 EW	13.28	33.92	34.26	0.30
	1807 EW	13.87	34.50		
	1807 LW	11.79	32.42	1807 LW	
	1807 LW	11.78	32.42	32.37	0.09
	1807 LW	11.63	32.27		
	Sigma Cell	6.65	27.28		
	1806 EW	13.89	34.52	1806 EW	
	1806 EW	13.54	34.17	34.39	0.20
	1806 EW	13.87	34.49		
	1806 LW	12.77	33.39	1806 LW	
	1806 LW	12.89	33.52	33.45	0.06
	1806 LW	12.81	33.44		
	Sigma Cell	6.78	27.41		
	1805 EW	14.37	35.08	1805 EW	
	1805 EW	15.44	36.15	35.64	0.54
	1805 EW	14.99	35.70		
	1805 LW	10.55	31.26	1805 LW	
	1805 LW	10.42	31.13	31.28	0.16
	1805 LW	10.74	31.45		
	Sigma Cell	6.48	27.19		
	1804 EW	13.48	34.22	1804 EW	
	1804 EW	14.00	34.74	34.42	0.28
	1804 EW	13.55	34.30		
	1804 LW	11.95	32.69	1804 LW	
	1804 LW	12.59	33.33	33.03	0.32

	1804 LW	12.33	33.07		
	Sigma Cell	6.71	27.46		
LL029B	Sample (02-12-04)				
	Sigma Cell	7.78			
	Sigma Cell	7.81			
	Sigma Cell	7.98			
	1803 EW	14.34	33.83	1803 EW	
	1803 EW	13.92	33.41	33.82	0.41
	1803 EW	14.73	34.22		
	1803 LW	12.01	31.50	1803 LW	
	1803 LW	12.14	31.63	31.51	0.11
	1803 LW	11.92	31.41		
	Sigma Cell	7.82	27.31		
	1802 EW	14.15	33.62	1802 EW	0.10
	1802 EW	14.28	33.76	33.65	
	1802 EW	14.09	33.57		
	1802 LW	12.18	31.66	1802 LW	0.55
	1802 LW	11.85	31.32	31.79	
	1802 LW	12.93	32.40		
	Sigma Cell	7.90	27.38		
	1801 EW	15.36	34.73	1801 EW	0.30
	1801 EW	14.84	34.21	34.39	
	1801 EW	14.84	34.22		
	1801 LW	13.27	32.65	1801 LW	0.32
	1801 LW	12.64	32.01	32.35	
	1801 LW	13.02	32.39		
	Sigma Cell	8.03	27.40		
	1800 EW	15.38	34.62	1800 EW	0.39
	1800 EW	14.88	34.12	34.54	
	1800 EW	15.65	34.89		
	1800 LW	13.19	32.43	1800 LW	0.42
	1800 LW	12.71	31.95	31.99	
	1800 LW	12.35	31.59		
	Sigma Cell	8.17	27.41		
	1799 EW	17.56	36.80	1799 EW	0.13
	1799 EW	17.75	36.98	36.84	
	1799 EW	17.51	36.74		
	1799 LW	13.62	32.85	1799 LW	0.33
	1799 LW	14.19	33.42	33.04	
	1799 LW	13.61	32.85		
	Sigma Cell	8.07	27.30		
	1798 EW	15.59	34.27	1798 EW	0.51
	1798 EW	16.25	34.94	34.39	

	1798 EW	15.26	33.95		
	1798 LW	13.54	32.23	1798 LW	0.22
	1798 LW	13.75	32.43	32.44	
	1798 LW	13.98	32.67		
	Sigma Cell	8.95	27.63		
LL029B	Sample (02-13-04)				
	Sigma Cell	8.92			
	Sigma Cell	8.92			
	Sigma Cell	8.30			
	1797 EW	17.51	36.19	1797 EW	
	1797 EW	17.38	36.06	36.14	0.07
	1797 EW	17.47	36.16		
	1797 LW	13.74	32.43	1797 LW	0.57
	1797 LW	14.55	33.24	32.60	
	1797 LW	13.45	32.13		
	Sigma Cell	8.60	27.28		
	1796 EW	15.77	34.42	1796 EW	0.07
	1796 EW	15.88	34.53	34.46	
	1796 EW	15.77	34.42		
	1796 LW	13.20	31.86	1796 LW	0.11
	1796 LW	13.40	32.05	31.93	
	1796 LW	13.23	31.88		
	Sigma Cell	8.78	27.43		
	1795 EW	17.31	35.80	1795 EW	0.14
	1795 EW	17.15	35.64	35.66	
	1795 EW	17.04	35.53		
	1795 LW	12.71	31.20	1795 LW	0.27
	1795 LW	13.08	31.57	31.27	
	1795 LW	12.56	31.05		
	Sigma Cell	8.92	27.41		
LL029B	Sample (02-14-04)				
	Sigma Cell	8.29			
	Sigma Cell	8.42			
	Sigma Cell	8.15			
	1794 EW	16.87	36.17	1794 EW	0.29
	1794 EW	17.28	36.59	36.49	
	1794 EW	17.38	36.72		
	1794 LW	13.40	32.75	1794 LW	0.15
	1794 LW	13.16	32.53	32.59	
	1794 LW	13.08	32.48		
	Sigma Cell	7.84	27.26		
	1793 EW	16.98	36.36	1793 EW	0.61

	1793 EW	17.03	36.40	36.73	
	1793 EW	18.07	37.43		
	1793 ELW	12.01	31.36	1793 ELW	0.14
	1793 ELW	11.89	31.23	31.22	
	1793 ELW	11.75	31.07		
	1793 LLW	13.42	32.73	1793 LLW	0.22
	1793 LLW	13.59	32.90	32.70	
	1793 LLW	13.18	32.47		
	Sigma Cell	8.07	27.35		
	1792 EW	16.24	35.43	1792 EW	0.39
	1792 EW	15.48	34.66	35.00	
	1792 EW	15.76	34.93		
	1792 LW	13.83	32.98	1792 LW	0.02
	1792 LW	13.81	32.96	32.98	
	1792 LW	13.85	32.99		
	Sigma Cell	8.22	27.35		
	1791 EW	15.72	34.84	1791 EW	0.07
	1791 EW	15.84	34.97	34.93	
	1791 EW	15.84	34.97		
	1791 LW	13.80	32.93	1791 LW	0.44
	1791 LW	13.96	33.09	33.25	
	1791 LW	14.62	33.75		
	Sigma Cell	8.21	27.34		
	1790 EW	15.44	34.59	1790 EW	0.26
	1790 EW	15.21	34.36	34.60	
	1790 EW	15.72	34.87		
	1790 LW	14.39	33.54	1790 LW	0.43
	1790 LW	13.56	32.71	33.07	
	1790 LW	13.81	32.96		
	Sigma Cell	8.17	27.32		
LL029B	Sample (02-14b-04)				
	Sigma Cell	8.65			
	Sigma Cell	8.67			
	Sigma Cell	8.60			
	1789 EW	15.76	34.49	1789 EW	
	1789 EW	16.03	34.76	34.62	0.14
	1789 EW	15.88	34.61		
	1789 LW	13.91	32.64	1789 LW	
	1789 LW	14.11	32.84	32.77	0.12
	1789 LW	14.11	32.84		
	Sigma Cell	8.58	27.31		
	1788 EW	14.74	34.08	1788 EW	
	1788 EW	15.13	34.55	34.62	0.57

	1788 EW	15.72	35.22		
	1788 LW	13.36	32.93	1788 LW	
	1788 LW	12.95	32.58	32.82	0.21
	1788 LW	13.25	32.96		
	Sigma Cell	7.56	27.34		
	1787 EW	16.65	35.70	1787 EW	
	1787 EW	16.75	35.71	35.86	0.26
	1787 EW	17.28	36.16		
	1787 LW	15.94	34.73	1787 LW	
	1787 LW	16.11	34.80	34.75	0.05
	1787 LW	16.12	34.71		
	Sigma Cell	8.83	27.34		
	1786 EW	16.73	35.14	1786 EW	
	1786 EW	16.53	34.94	34.92	0.22
	1786 EW	16.31	34.69		
	1786 LW	13.83	32.20	1786 LW	
	1786 LW	13.83	32.19	32.30	0.18
	1786 LW	14.16	32.51		
	Sigma Cell	9.00	27.34		
	1785 EW	19.11	37.49	1785 EW	
	1785 EW	19.58	37.96	37.59	0.33
	1785 EW	18.94	37.32		
	1785 LW	15.09	33.47	1785 LW	
	1785 LW	15.50	33.88	33.72	0.22
	1785 LW	15.43	33.81		
	Sigma Cell	8.92	27.30		
	1784 EW	16.74	35.24	1784 EW	
	1784 EW	17.04	35.54	35.53	0.28
	1784 EW	17.29	35.80		
	1784 LW	14.80	33.33	1784 LW	
	1784 LW	14.50	33.03	33.28	0.23
	1784 LW	14.94	33.49		
	Sigma Cell	8.79	27.34		
LL029B	Sample (02-15-04)				
	Sigma Cell	8.64			
	Sigma Cell	9.00			
	Sigma Cell	8.91			
	1783 EW	17.99	36.46	1783 EW	
	1783 EW	18.09	36.56	36.59	0.15
	1783 EW	18.29	36.75		
	1783 LW	15.29	33.75	1783 LW	
	1783 LW	15.17	33.63	33.70	0.06
	1783 LW	15.25	33.71		

	Sigma Cell	8.90	27.37		
	1782 EW	16.72	35.05	1782 EW	
	1782 EW	16.82	35.05	35.07	0.03
	1782 EW	16.99	35.11		
	1782 LW	15.00	33.02	1782 LW	
	1782 LW	14.48	32.38	32.78	0.35
	1782 LW	15.15	32.94		
	Sigma Cell	8.69	26.38		
	1781 EW	17.16	35.66	1781 EW	
	1781 EW	17.63	36.11	35.69	0.40
	1781 EW	16.85	35.31		
	1781 LW	16.11	34.55	1781 LW	
	1781 LW	15.21	33.63	34.00	0.49
	1781 LW	15.42	33.82		
	Sigma Cell	8.96	27.34		
LL029B	Sample (04-05a-04)				
	Sigma Cell	9.32			
	Sigma Cell	9.18			
	Sigma Cell	9.28			
	Sigma Cell	9.06			
	1780 EW	16.87	34.90	1780 EW	0.14
	1780 EW	16.63	34.66	34.82	
	1780 EW	16.88	34.90		
	1780 ELW	12.45	30.47	1780 ELW	0.10
	1780 ELW	12.59	30.62	30.50	
	1780 ELW	12.40	30.43		
	1780 LLW	14.14	32.17	1780 LLW	0.25
	1780 LLW	14.31	32.33	32.38	
	1780 LLW	14.63	32.65		
LL029B	Sample (04-05a-04)				
	Sigma Cell	10.29			
	Sigma Cell	10.50			
	Sigma Cell	10.49			
	1778 EW	17.83	34.76	1778 EW	
	1778 EW	17.83	34.76	34.53	0.39
	1778 EW	17.16	34.09		
	1778 LW	14.70	31.64	1778 LW	
	1778 LW	15.47	32.41	31.66	0.73
	1778 LW	14.00	30.94		
	Sigma Cell	10.40	27.34		
	1777 EW	18.30	35.60	1777 EW	
	1777 EW	18.74	36.09	36.45	1.08

	1777 EW	20.27	37.67		
	1777 LW	17.78	35.21	1777 LW	
	1777 LW	17.68	35.16	34.68	0.88
	1777 LW	16.14	33.66		
	Sigma Cell	9.77	27.34		
	1779 EW	17.70	35.16	1779 EW	
	1779 EW	17.54	34.98	34.99	0.17
	1779 EW	17.39	34.82		
	1779 LW	14.33	31.75	1779 LW	
	1779 LW	14.55	31.95	31.84	0.11
	1779 LW	14.41	31.81		
	Sigma Cell	9.96	27.34		
	1776 EW	17.28	34.65	1776 EW	
	1776 EW	17.61	34.97	34.51	0.54
	1776 EW	16.58	33.92		
	1776 LW	14.93	32.26	1776 LW	
	1776 LW	15.24	32.55	32.30	0.23
	1776 LW	14.80	32.10		
LL029B	Sample (05-15-04)				
	Sigma Cell	6.58			
	Sigma Cell	5.71			
	Sigma Cell	6.21			
	1775 EW	13.99	35.11	1775 EW	0.27
	1775 EW	13.62	34.74	34.81	
	1775 EW	13.47	34.59		
	1775 LW	11.93	33.04	1775 LW	0.57
	1775 LW	12.36	33.47	33.56	
	1775 LW	13.07	34.16		
	Sigma Cell	6.25	27.34		
	1774 EW	13.69	34.66	1774 EW	0.06
	1774 EW	13.65	34.60	34.60	
	1774 EW	13.60	34.53		
	1774 LW	11.49	32.40	1774 LW	0.50
	1774 LW	11.44	32.34	32.66	
	1774 LW	12.35	33.23		
	Sigma Cell	6.47	27.34		
	1773 EW	13.46	34.21	1773 EW	0.33
	1773 EW	13.91	34.65	34.28	
	1773 EW	13.27	33.99		
	1773 LW	10.03	30.74	1773 LW	0.28
	1773 LW	10.61	31.30	31.04	
	1773 LW	10.39	31.08		
	Sigma Cell	6.67	27.34		

	1772 EW	13.53	34.18	1772 EW	0.40
	1772 EW	13.79	34.44	34.53	
	1772 EW	14.31	34.96		
	1772 LW	11.98	32.63	1772 LW	0.32
	1772 LW	11.88	32.52	32.76	
	1772 LW	12.48	33.12		
	Sigma Cell	6.70	27.34		
	1771 EW	12.97	33.74	1771 EW	0.19
	1771 EW	12.93	33.72	33.62	
	1771 EW	12.59	33.40		
	1771 LW	11.68	32.51	1771 LW	0.33
	1771 LW	11.09	31.94	32.31	
	1771 LW	11.63	32.49		
	Sigma Cell	6.46	27.34		
	1770 EW	14.24	35.00	1770 EW	0.32
	1770 EW	14.63	35.37	35.03	
	1770 EW	14.01	34.73		
	1770 LW	11.71	32.42	1770 LW	0.37
	1770 LW	11.11	31.81	32.23	
	1770 LW	11.78	32.46		
	Sigma Cell	6.68	27.34		

Orgnanic and Inorganic Standards

STD's	Sample (6-28-03)				
Correct	sigma cell	9.25			
Value	sigma cell	9.35			
	sigma cell	9.54			
	sigma cell	9.66			
	sigma cell	9.62			
	SIRFER	11.27	28.89		0.21
	SIRFER	10.87	28.49		
28.3	SIRFER	11.39	29.01		
	SIRFER	11.00	28.62		
	SIRFER	11.13	28.75		
	sigma cell	9.82			
	Jahren	11.90	29.51		0.17
	Jahren	11.68	29.29		
29.3	Jahren	11.45	29.06		
	Jahren	11.52	29.13		
	Jahren	11.65	29.26		

	sigma cell	9.64		
21.4	CHCC (f)	3.72	21.41	0.26
	CHCC (f)	3.71	21.40	
	CHCC (f)	lost	lost	
	CHCC (f)	4.21	21.90	
	CHCC (f)	3.63	21.33	
28.6	NBS-19	9.75	27.45	0.36
	NBS-19	10.48	28.18	
	NBS-19	10.32	28.02	
	NBS-19	10.81	28.51	
	NBS-19	10.57	28.27	
	NBS-19	10.16	27.86	
	NBS-19	11.12	28.82	
	NBS-19	10.99	28.69	
	NBS-19	10.64	28.34	
	NBS-19	10.49	28.19	
	NBS-19	10.57	28.27	
	NBS-19	11.03	28.73	
	NBS-19	10.71	28.41	
	NBS-19	11.10	28.80	
	NBS-19	11.02	28.72	
	NBS-19	10.75	28.45	
	NBS-19	10.88	28.58	
	NBS-19	10.98	28.68	
	sigma cell	10.10		

Appendix 2. Raw and Corrected Oxygen Isotope Values 1580-1650

(EW=earlywood; LW=latewood)

	Sample (6-10-03)	Raw ^{18}O Values	Corrected ^{18}O Values	EW/LW Average	Standard Deviation
	sigma cell	7.999			
LL	sigma cell	8.029			7.88
CO39A	sigma cell	7.615			
	1650 EW	12.695	32.39	1650 EW	0.24
	1650 EW	11.821	31.42	31.89	
	1650 EW	12.247	31.86		
	1650 LW	11.83	31.45	1650 LW	0.54
	1650 LW	10.777	30.41	31.00	
	1650 LW	11.496	31.13		
	1649 EW	15.5	35.15	1649 EW	0.47
	1649 EW	15.197	34.85	35.26	
	1649 EW	16.116	35.78		
	1649 LW	13.072	32.75	1649 LW	0.31
	1649 LW	12.447	32.13	32.44	
	1649 LW	12.728	32.42		
	sigma cell	7.635	27.34		
	1648 EW	11.426	31.14	1648 EW	0.68
	1648 EW	12.721	32.44	31.90	
	1648 EW	12.413	32.13		
	1648 LW	13.962	33.68	1648 LW	0.18
	1648 LW	13.916	33.63	33.76	
	1648 LW	14.243	33.96		
	1647 EW	14.322	34.04	1647 EW	0.20
	1647 EW	13.935	33.65	33.88	
	1647 EW	14.243	33.96		
	1647 LW	11.935	31.65	1647 LW	0.22
	1647 LW	12.364	32.08	31.88	
	1647 LW	12.176	31.90		
	sigma cell	7.619	27.34		
	1646 EW	12.527	32.02	1646 EW	0.21
	1646 EW	12.942	32.44	32.21	
	1646 EW	12.682	32.16		
	1646 LW	12.512	31.98	1646 LW	0.26
	1646 LW	12.889	32.34	32.16	
	1646 LW	lost	lost		
	1645 EW	13.383	32.80	1645 EW	0.96
	1645 EW	15.285	34.69	33.83	
	1645 EW	14.623	34.01		
	1645 LW	14.434	33.81	1645 LW	0.33
	1645 LW	14.043	33.40	33.75	

	1645 LW	14.702	34.05		
	sigma cell	8.011	27.34		
	1644 EW	15.173	34.49	1644 EW	0.22
	1644 EW	15.423	34.72	34.50	
	1644 EW	14.988	34.29		
LL	Sample (6-10-03)				
CO39A	sigma cell	8.827			
	sigma cell	9.235			
	sigma cell	9.469			
	1644 LW	14.749	32.68	1644 LW	0.28
	1644 LW	14.859	32.77	32.57	
	1644 LW	14.358	32.25		
	1643 EW	16.923	34.80	1643 EW	0.23
	1643 EW	17.32	35.18	34.91	
	1643 EW	16.928	34.77		
	1643 LW	15.75	33.57	1643 LW	0.43
	1643 LW	14.97	32.77	33.27	
	1643 LW	15.674	33.46		
	sigma cell	9.647	27.41		
	sigma cell	9.57	27.32		
	sigma cell	9.609	27.34		
	1642 EW	15.844	33.46	1642 EW	0.78
	1642 EW	16.659	34.27	34.25	
	1642 EW	17.413	35.01		
	1642 LW	13.859	31.45	1642 LW	0.24
	1642 LW	14.335	31.92	31.67	
	1642 LW	14.064	31.64		
	sigma cell	9.781	27.35		
	sigma cell	9.655			
	1641 EW	14.936	32.50	1641 EW	0.35
	1641 EW	15.355	32.91	32.87	
	1641 EW	15.641	33.19		
	1641 LW	17.282	34.83	1641 LW	0.81
	1641 LW	16.869	34.41	34.16	
	1641 LW	15.728	33.26		
	sigma cell	9.818	27.34		
	1640 EW	16.399	33.81	1640 EW	0.18
	1640 EW	16.048	33.44	33.64	
	1640 EW	16.287	33.66		
	1640 LW	16.607	33.97	1640 LW	0.13
	1640 LW	16.484	33.83	33.83	
	1640 LW	16.369	33.70		
	sigma cell	10.021	27.34		

	1639 EW	16.623	34.05	1639 EW	0.59
	1639 EW	16.905	34.35	34.53	
	1639 EW	17.731	35.19		
	1639 LW	15.266	32.73	1639 LW	0.42
	1639 LW	15.894	33.38	33.21	
	1639 LW	16.02	33.52		
	sigma cell	9.831	27.34		
	1638 EW	15.868	33.39	1638 EW	0.04
	1638 EW	15.844	33.38	33.41	
	1638 EW	15.913	33.46		
LL	Sample (6-10-03)				
CO39A	sigma cell	9.829			
	sigma cell	9.285			
	sigma cell	8.992			
	1638 LW	15.245	33.47	1638 LW	0.86
	1638 LW	15.084	33.36	33.91	
	1638 LW	16.581	34.91		
	sigma cell	8.961	27.34		
	1637 EW	16.189	34.43	1637 EW	0.55
	1637 EW	16.039	34.27	34.66	
	1637 EW	17.075	35.29		
	1637 LW	17.148	35.34	1637 LW	0.89
	1637 LW	15.541	33.72	34.74	
	1637 LW	16.994	35.16		
	sigma cell	9.194	27.34		
	1636 EW	16.032	34.34	1636 EW	0.07
	1636 EW	16.115	34.45	34.37	
	1636 EW	15.967	34.32		
	1636 LW	17.825	36.20	1636 LW	0.09
	1636 LW	17.989	36.39	36.28	
	1636 LW	17.841	36.26		
	sigma cell	8.902	27.34		
	1635 EW	15.666	34.13	1635 EW	0.22
	1635 EW	15.499	33.97	34.17	
	1635 EW	15.936	34.41		
	1635 LW	16.36	34.83	1635 LW	0.31
	1635 LW	15.839	34.31	34.48	
	1635 LW	15.813	34.29		
	sigma cell	8.858	27.34		
	1634 EW	15.806	34.19	1634 EW	0.26
	1634 EW	15.609	33.98	34.22	
	1634 EW	16.139	34.50		
	1634 LW	15.439	33.78	1634 LW	0.49

	1634 LW	15.982	34.31	34.28	
	1634 LW	16.435	34.75		
	sigma cell	9.034	27.34		
	1633 EW	18.463	36.75	1633 EW	0.90
	1633 EW	17.153	35.44	35.75	
	1633 EW	16.749	35.04		
	1633 LW	14.135	32.43	1633 LW	0.40
	1633 LW	14.706	33.00	32.87	
	1633 LW	14.902	33.19		
	sigma cell	9.066	27.36		
LL	Sample (6-10-03)				
CO39A	sigma cell	9.703			
	sigma cell	9.742			
	sigma cell	9.83			
	1632 EW	18.382	35.96	1632 EW	0.64
	1632 EW	18.741	36.32	35.79	
	1632 EW	17.506	35.09		
	1632 LW	15.259	32.84	1632 LW	0.18
	1632 LW	14.994	32.57	32.78	
	1632 LW	15.349	32.93		
	sigma cell	9.759	27.34		
	1631 EW	18.523	35.94	1631 EW	0.36
	1631 EW	18.029	35.42	35.68	
	1631 EW	lost	lost		
	1631 LW	16.147	33.50	1631 LW	0.43
	1631 LW	15.853	33.18	33.57	
	1631 LW	16.726	34.04		
	sigma cell	10.051	27.34		
	1630 EW	17.567	34.86	1630 EW	0.15
	1630 EW	17.277	34.57	34.74	
	1630 EW	17.499	34.79		
	1630 LW	16.779	34.07	1630 LW	0.59
	1630 LW	17.653	34.94	34.73	
	1630 LW	17.892	35.18		
	sigma cell	10.077	27.37		
	1629 EW	18.133	35.48	1629 EW	0.38
	1629 EW	18.658	36.02	35.90	
	1629 EW	18.837	36.21		
	1629 LW	15.859	33.24	1629 LW	0.70
	1629 LW	16.517	33.91	33.22	
	1629 LW	15.11	32.52		
	sigma cell	9.923	27.34		
	1628 EW	18.042	35.36	1628 EW	0.26

	1628 EW	17.785	35.09	35.10	
	1628 EW	17.554	34.85		
	1628 LW	15.368	32.65	1628 LW	0.20
	1628 LW	15.045	32.31	32.42	
	1628 LW	15.049	32.30		
	sigma cell	10.25	27.49		
	sigma cell	10.114	27.34		
	sigma cell	9.929	27.15		
LL	Sample (6-10-03)				
CO39A	Sigma Cell	6.158			
	Sigma Cell	6.351			
	Sigma Cell	6.522			
	Sigma Cell	6.46			
	1626 EW	14.945	36.18	1626 EW	0.48
	1626 EW	15.568	36.83	36.30	
	1626 EW	14.594	35.89		
	1626 LW	14.242	35.57	1626 LW	0.74
	1626 LW	12.948	34.31	34.71	
	1626 LW	12.86	34.26		
	Sigma Cell	5.912	27.34		
	1625 EW	14.971	36.48	1625 EW	0.35
	1625 EW	15.344	37.08	36.88	
	1625 EW	15.553	37.09		
	1625 LW	12.978	34.52	1625 LW	0.27
	1625 LW	13.145	34.70	34.46	
	1625 LW	12.601	34.17		
	Sigma Cell	5.762	27.34		
	1624 EW	13.996	35.20	1624 EW	0.21
	1624 EW	14.276	35.43	35.42	
	1624 EW	14.519	35.62		
	1624 LW	11.766	32.82	1624 LW	0.77
	1624 LW	11.126	32.14	32.08	
	1624 LW	10.325	31.29		
	Sigma Cell	6.423	27.34		
	1623 EW	14.174	35.08	1623 EW	0.73
	1623 EW	14.136	35.04	34.64	
	1623 EW	12.896	33.80		
	1623 LW	12.429	33.34	1623 LW	0.51
	1623 LW	13.068	33.98	33.42	
	1623 LW	12.05	32.96		
	Sigma Cell	6.441	27.35		
	1622 EW	12.303	32.96	1622 EW	0.18

	1622 EW	12.394	33.02	33.09	
	1622 EW	12.701	33.29		
	1622 LW	12.847	33.41	1622 LW	0.14
	1622 LW	12.615	33.15	33.26	
	1622 LW	12.716	33.22		
	Sigma Cell	6.87	27.34		
	1627 EW	14.051	34.81	1627 EW	0.12
	1627 EW	13.808	34.60	34.67	
	1627 EW	13.769	34.60		
	1627 LW	13.465	34.33	1627 LW	0.08
	1627 LW	13.342	34.24	34.33	
	1627 LW	13.472	34.41		
	Sigma Cell	6.368	27.34		
LL CO39A	Sample (4-02-04)				
	Sigma Cell	8.997			
	Sigma Cell	8.413			
	Sigma Cell	8.272			
	1621 LW	15.251	34.58	1621 LW	0.35
	1621 LW	15.219	34.66	34.42	
	1621 LW	14.466	34.02		
	Sigma Cell	7.681	27.34		
	1620 EW	16.29	35.78	1620 EW	0.07
	1620 EW	16.317	35.78	35.74	
	1620 EW	16.211	35.66		
	1620 LW	12.65	32.07	1620 LW	0.45
	1620 LW	13.243	32.65	32.56	
	1620 LW	13.573	32.96		
	Sigma Cell	7.979	27.34		
	1619 EW	16.39	35.86	1619 EW	0.42
	1619 EW	15.81	35.30	35.76	
	1619 EW	16.615	36.12		
	1619 LW	14.126	33.64	1619 LW	0.48
	1619 LW	14.08	33.61	33.90	
	1619 LW	14.91	34.45		
	Sigma Cell	7.781	27.34		
	1618 EW	15.71	35.14	1618 EW	0.30
	1618 EW	15.204	34.62	34.97	
	1618 EW	15.742	35.14		
	1618 LW	12.454	31.84	1618 LW	1.06
	1618 LW	14.582	33.95	32.93	
	1618 LW	13.644	32.99		

	Sigma Cell	8.007	27.34		
	1617 EW	13.847	33.72	1617 EW	0.91
	1617 EW	15.531	35.44	34.76	
	1617 EW	15.183	35.12		
	1617 LW	12.479	32.44	1617 LW	0.31
	1617 LW	13.02	33.01	32.66	
	1617 LW	12.514	32.54		
	Sigma Cell	lost	lost		
	1616 EW	16.311	36.39	1616 EW	0.18
	1616 EW	16.039	36.15	36.19	
	1616 EW	15.894	36.03		
	1616 LW	11.791	31.96	1616 LW	0.62
	1616 LW	12.336	32.53	32.56	
	1616 LW	12.97	33.19		
	Sigma Cell	7.262	27.51		
	Sigma Cell	6.687	26.97		
	1621 EW	12.083	32.39	1621 EW	0.47
	1621 EW	12.488	32.82	32.85	
	1621 EW	12.972	33.34		
LL	Sample (4-03b-04)				
CO39A	Sigma Cell	7.027			
	Sigma Cell	7.253			
	Sigma Cell	6.974			
	1615 EW	13.513	34.11	1615 EW	0.42
	1615 EW	14.293	34.93	34.57	
	1615 EW	13.982	34.66		
	1615 LW	13.185	33.91	1615 LW	0.17
	1615 LW	13.205	33.97	33.85	
	1615 LW	12.844	33.65		
	Sigma Cell	6.487	27.34		
	1614 EW	14.345	34.97	1614 EW	0.47
	1614 EW	13.594	34.19	34.73	
	1614 EW	14.459	35.03		
	1614 LW	13.823	34.37	1614 LW	0.23
	1614 LW	14.296	34.81	34.62	
	1614 LW	14.184	34.67		
	Sigma Cell	6.882	27.34		
	1613 EW	13.69	34.25	1613 EW	0.11
	1613 EW	13.845	34.42	34.29	
	1613 EW	13.632	34.22		
	1613 LW	13.845	34.44	1613 LW	0.29
	1613 LW	13.261	33.87	34.13	
	1613 LW	13.444	34.07		

	Sigma Cell	6.704	27.34		
	1612 EW	10.966	31.55	1612 EW	0.36
	1612 EW	11.634	32.21	31.96	
	1612 EW	11.572	32.14		
	1612 LW	13.534	34.09	1612 LW	0.49
	1612 LW	13.198	33.75	33.66	
	1612 LW	12.583	33.13		
	Sigma Cell	6.8	27.34		
	1611 EW	15.283	36.01	1611 EW	0.46
	1611 EW	14.595	35.34	35.49	
	1611 EW	14.361	35.13		
	1611 LW	12.298	33.09	1611 LW	0.29
	1611 LW	12.279	33.09	33.26	
	1611 LW	12.759	33.60		
	Sigma Cell	6.481	27.34		
	1610 EW	12.752	33.11	1610 EW	0.42
	1610 EW	13.376	33.67	33.57	
	1610 EW	13.697	33.93		
	1610 LW	13.101	33.27	1610 LW	0.27
	1610 LW	13.643	33.75	33.44	
	1610 LW	13.265	33.31		
	Sigma Cell	7.36	27.34		
LL	Sample (4-04a-04)				
CO39A	Sigma Cell	8.893			
	Sigma Cell	9.038			
	Sigma Cell	8.879			
	1609 EW	16.24	34.62	1609 EW	0.23
	1609 EW	16.141	34.52	34.70	
	1609 EW	16.578	34.96		
	1609 LW	14.775	33.15	1609 LW	0.31
	1609 LW	14.821	33.20	33.35	
	1609 LW	15.331	33.70		
	1608 EW	17.315	35.69	1608 EW	0.46
	1608 EW	16.397	34.77	35.20	
	1608 EW	16.772	35.14		
	1608 LW	14.976	33.34	1608 LW	0.07
	1608 LW	14.839	33.20	33.28	
	1608 LW	14.927	33.29		
	Sigma Cell	8.978	27.34		
	1607 EW	18.271	36.64	1607 EW	0.29
	1607 EW	17.799	36.17	36.51	
	1607 EW	18.327	36.70		
	1607 LW	15.628	34.01	1607 LW	0.35

	1607 LW	16.284	34.66	34.27	
	1607 LW	15.753	34.13		
	Sigma Cell	8.958	27.34		
	1606 EW	17.864	36.29	1606 EW	0.50
	1606 EW	17.942	36.37	36.62	
	1606 EW	18.761	37.20		
	1606 LW	15.792	34.23	1606 LW	0.01
	1606 LW	15.765	34.21	34.22	
	1606 LW	15.767	34.22		
	Sigma Cell	8.883	27.34		
	1605 EW	17.512	35.71	1605 EW	0.28
	1605 EW	18.098	36.26	35.95	
	1605 EW	17.755	35.88		
	1605 LW	15.309	33.40	1605 LW	0.32
	1605 LW	15.105	33.17	33.11	
	1605 LW	14.737	32.77		
	Sigma Cell	9.345	27.34		
	1604 EW	17.545	35.51	1604 EW	0.29
	1604 EW	17.51	35.44	35.64	
	1604 EW	18.081	35.98		
	1604 LW	15.532	33.40	1604 LW	0.15
	1604 LW	15.479	33.31	33.27	
	1604 LW	15.299	33.10		
	Benzoic Acid	8.962			
	Benzoic Acid	8.635			
	Benzoic Acid	8.054			
LL	Sample (4-04b-04)				
CO39A	Sigma Cell	7.402			
	Sigma Cell	7.01			
	Sigma Cell	7.718			
	1603 EW	14.3	34.56	1603 EW	0.30
	1603 EW	13.905	34.20	34.24	
	1603 EW	13.621	33.95		
	1603 LW	12.643	33.01	1603 LW	0.11
	1603 LW	12.805	33.21	33.08	
	1603 LW	12.583	33.02		
	Sigma Cell	6.863	27.34		
	1602 EW	14.473	35.11	1602 EW	0.05
	1602 EW	14.509	35.17	35.12	
	1602 EW	14.399	35.08		
	1602 LW	12.623	33.32	1602 LW	0.12
	1602 LW	12.422	33.14	33.19	
	1602 LW	12.369	33.11		

	Sigma Cell	6.583	27.34		
	1601 EW	15.908	36.53	1601 EW	0.15
	1601 EW	15.897	36.50	36.43	
	1601 EW	15.667	36.25		
	1601 LW	11.733	32.30	1601 LW	0.19
	1601 LW	11.493	32.04	32.25	
	1601 LW	11.883	32.42		
	Sigma Cell	6.823	27.34		
	1600 EW	15.099	35.48	1600 EW	0.37
	1600 EW	15.393	35.76	35.81	
	1600 EW	15.86	36.21		
	1600 LW	13.904	34.23	1600 LW	0.42
	1600 LW	13.088	33.40	33.79	
	1600 LW	13.432	33.73		
	Sigma Cell	7.061	27.34		
	1599 EW	13.825	34.06	1599 EW	0.26
	1599 EW	14.225	34.45	34.35	
	1599 EW	14.314	34.54		
	1599 LW	12.041	32.26	1599 LW	0.12
	1599 LW	11.895	32.11	32.24	
	1599 LW	12.132	32.34		
	Sigma Cell	7.138	27.34		
	1598 EW	15.63	35.48	1598 EW	0.74
	1598 EW	15.444	35.25	34.94	
	1598 EW	14.328	34.09		
	1598 LW	12.935	32.65	1598 LW	0.11
	1598 LW	12.759	32.43	32.54	
	1598 LW	12.887	32.52		
	Sigma Cell	7.752	27.34		
LL	Sample (4-05a-04)				
CO39A	Sigma Cell	9.317			
	Sigma Cell	9.184			
	Sigma Cell	9.128			
	1597 EW	17.283	35.50	1597 EW	0.06
	1597 EW	17.383	35.61	35.56	
	1597 EW	17.338	35.58		
	1597 LW	16.072	34.32	1597 LW	0.81
	1597 LW	16.81	35.07	35.11	
	1597 LW	17.66	35.94		
	Sigma Cell	9.059	27.34		
	Run Terminated				
LL	Sample (5-14-04)				

CO39A	Sigma Cell	7.957			
	Sigma Cell	7.452	7.65		
	Sigma Cell	7.481	19.69		
	1596 EW	17.764	37.46	1596 EW	0.16
	1596 EW	17.605	37.29	37.29	
	1596 EW	17.442	37.13		
	1596 LW	14.536	34.22	1596 LW	0.46
	1596 LW	13.652	33.33	33.71	
	1596 LW	13.907	33.59		
	Sigma Cell	7.663	27.34		
	1595 EW	16.643	36.59	1595 EW	0.14
	1595 EW	16.669	36.65	36.70	
	1595 EW	16.848	36.86		
	1595 LW	14.966	35.02	1595 LW	0.51
	1595 LW	15.133	35.22	34.83	
	1595 LW	14.138	34.26		
	Sigma Cell	7.189	27.34		
	1594 EW	15.381	35.46	1594 EW	0.27
	1594 EW	15.881	35.95	35.76	
	1594 EW	15.828	35.89		
	1594 LW	12.778	32.83	1594 LW	0.08
	1594 LW	12.761	32.80	32.77	
	1594 LW	12.654	32.69		
	Sigma Cell	7.318	27.34		
	1593 EW	17.322	37.14	1593 EW	0.27
	1593 EW	16.95	36.76	36.95	
	1593 EW	Lost	Lost		
	1593 LW	11.898	31.68	1593 LW	0.36
	1593 LW	12.565	32.33	32.09	
	1593 LW	12.52	32.27		
	Sigma Cell	Lost	Lost		
	1592 EW	14.671	34.40	1592 EW	0.14
	1592 EW	14.846	34.56	32.09	
	1592 EW	14.984	34.68		
	1592 LW	12.784	32.47	1592 LW	0.38
	1592 LW	12.151	31.82	32.03	
	1592 LW	12.148	31.81		
	Sigma Cell	7.695	27.34		
	1591 EW	17.211	37.15	1591 EW	0.37
	1591 EW	16.546	36.53	36.73	
	1591 EW	16.488	36.51		
	1591 LW	13.004	33.06	1591 LW	0.60
	1591 LW	11.762	31.85	32.46	
	1591 LW	12.326	32.45		

	Sigma Cell	7.174	27.34		
LL	Sample (5-14b-04)				
CO39A	Sigma Cell	8.589			
	Sigma Cell	8.711			
	Sigma Cell	8.837			
	1590 EW	18.607	37.02	1590 EW	0.19
	1590 EW	19.013	37.40	37.23	
	1590 EW	18.906	37.27		
	1590 LW	14.627	32.96	1590 LW	0.13
	1590 LW	14.886	33.19	33.04	
	1590 LW	14.689	32.97		
	Sigma Cell	9.085	27.34		
	1589 EW	15.584	33.99	1589 EW	0.17
	1589 EW	15.794	34.22	34.17	
	1589 EW	15.871	34.31		
	1589 LW	14.338	32.80	1589 LW	0.08
	1589 LW	14.3	32.78	32.74	
	1589 LW	14.149	32.64		
	Sigma Cell	8.826	27.34		
	1588 EW	16.657	35.00	1588 EW	0.33
	1588 EW	17.334	35.66	35.33	
	1588 EW	17.035	35.34		
	1588 LW	14.001	32.28	1588 LW	0.14
	1588 LW	14.298	32.56	32.42	
	1588 LW	14.178	32.42		
	Sigma Cell	9.123	27.34		
	1587 EW	17.95	36.40	1587 EW	0.22
	1587 EW	18.351	36.83	36.61	
	1587 EW	18.082	36.59		
	1587 LW	14.356	32.89	1587 LW	0.12
	1587 LW	14.549	33.11	32.98	
	1587 LW	14.332	32.93		
	Sigma Cell	8.716	27.34		
	1586 EW	16.901	35.31	1586 EW	0.09
	1586 EW	16.756	35.14	35.24	
	1586 EW	16.908	35.26		
	1586 LW	14.735	33.06	1586 LW	0.09
	1586 LW	14.718	33.02	33.09	
	1586 LW	14.921	33.19		
	Sigma Cell	9.094	27.34		
LL	Sample (5-14c-04)				

CO39A	Sigma Cell	6.262			
	Sigma Cell	6.085			
	Sigma Cell	6.221			
	1585 EW	13.715	35.00	1585 EW	0.07
	1585 EW	13.822	35.13	35.09	
	1585 EW	13.81	35.13		
	1585 LW	10.959	32.30	1585 LW	0.25
	1585 LW	10.941	32.30	32.15	
	1585 LW	10.492	31.86		
	Sigma Cell	5.952	27.34		
	1584 EW	14.083	35.26	1584 EW	0.40
	1584 EW	14.893	36.04	35.61	
	1584 EW	14.403	35.53		
	1584 LW	11.148	32.25	1584 LW	0.12
	1584 LW	11.181	32.25	32.32	
	1584 LW	11.413	32.46		
	Sigma Cell	6.321	27.34		
	1583 EW	14.171	35.31	1583 EW	0.09
	1583 EW	14	35.16	35.21	
	1583 EW	13.984	35.16		
	1583 LW	10.81	32.00	1583 LW	0.38
	1583 LW	10.585	31.79	32.11	
	1583 LW	11.314	32.53		
	Sigma Cell	6.107	27.34		
	1582 EW	13.003	33.85	1582 EW	0.07
	1582 EW	13.117	33.92	33.85	
	1582 EW	13.031	33.78		
	1582 LW	10.337	31.04	1582 LW	0.36
	1582 LW	10.118	30.77	31.10	
	1582 LW	10.873	31.48		
	Sigma Cell	6.78	27.34		
	1581 EW	14.501	35.47	1581 EW	0.12
	1581 EW	14.633	35.65	35.60	
	1581 EW	14.621	35.69		
	1581 LW	12.747	33.87	1581 LW	0.35
	1581 LW	13.284	34.46	34.27	
	1581 LW	13.276	34.50		
	Sigma Cell	6.067	27.34		
	1580 EW	14.418	35.52	1580 EW	0.26
	1580 EW	14.079	35.16	35.45	
	1580 EW	14.602	35.66		
	1580 LW	11.738	32.78	1580 LW	0.19
	1580 LW	11.379	32.40	32.58	
	1580 LW	11.561	32.56		

Sigma Cell	6.365	27.34

*Note: VSU is Valdosta State University and LL is Lake Louise

Vita

Dana Lynette Miller was born in Chattanooga, Tennessee on the fifth of February 1974. She was raised and educated in Manchester, Tennessee, where she graduated from Manchester Central High School in 1992. She received her B.S. in geology from Tennessee Technological University in Cookeville, Tennessee in 1997. She worked for a year as a mine geologist in Gordonsville, Tennessee for Savage Zinc, Inc. She began graduate school in the geological sciences in 1998 at the University of Tennessee where she received her Master's degree in 2000 and remained at the Department of Earth and Planetary Sciences to complete her Ph.D.